



Fermi
Gamma-ray Space Telescope

Gamma-ray sources and signatures

Elizabeth Ferrara

Fermi Science Support Center
(on behalf of a cast of hundreds)

2013 Fermi Summer School
May 28 – June 7

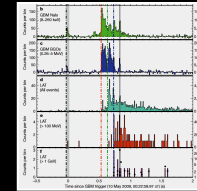
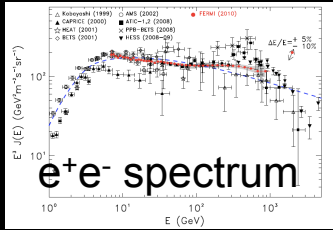


Fermi is an All-sky explorer

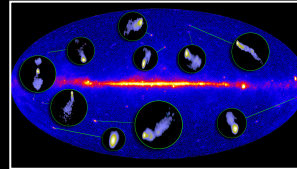
- **Fermi has been operating for more than four years, primarily in all-sky survey mode**
- **Persistent gamma-ray sources:**
 - **List of bright LAT sources – 205 @ $> 10\sigma$ in 3 months**
 - **Two LAT point source catalogs**
 - **1451 sources after 11 months, 1873 after 24 months**
 - **Two catalogs of LAT-detected AGN**
 - **Two catalogs of LAT-detected pulsars**
 - **Catalog of GBM Earth-occultation sources**
- **Transient gamma-ray sources:**
 - **Two catalogs of GBM-detected GRBs**
 - **Catalog of LAT-detected GRBs**
 - **List of GBM-detected TGFs**

<http://fermi.gsfc.nasa.gov/ssc/data/access/>
<http://www-glast.stanford.edu/cgi-bin/pubpub>

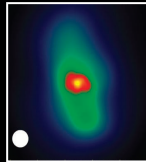
Fermi Reveals the Very High Energy Universe



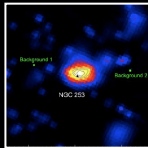
GRBs



Blazars

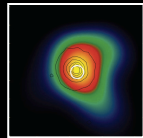
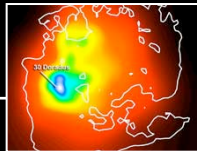


Radio Galaxies



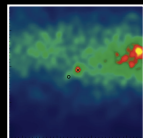
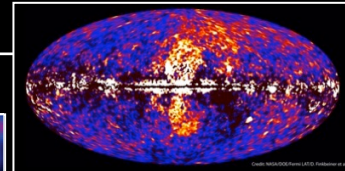
Starburst Galaxies

LMC & SMC



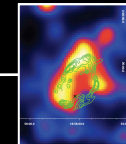
Globular Clusters

Fermi Bubbles

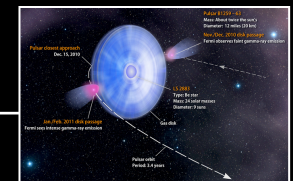


Nova

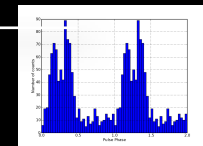
SNRs & PWN



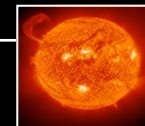
γ -ray Binaries



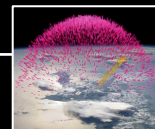
Pulsars: isolated, binaries, & MSPs



Sun: flares & CR interactions



Terrestrial γ -ray Flashes



Unassociated Sources
(577 of 1873)

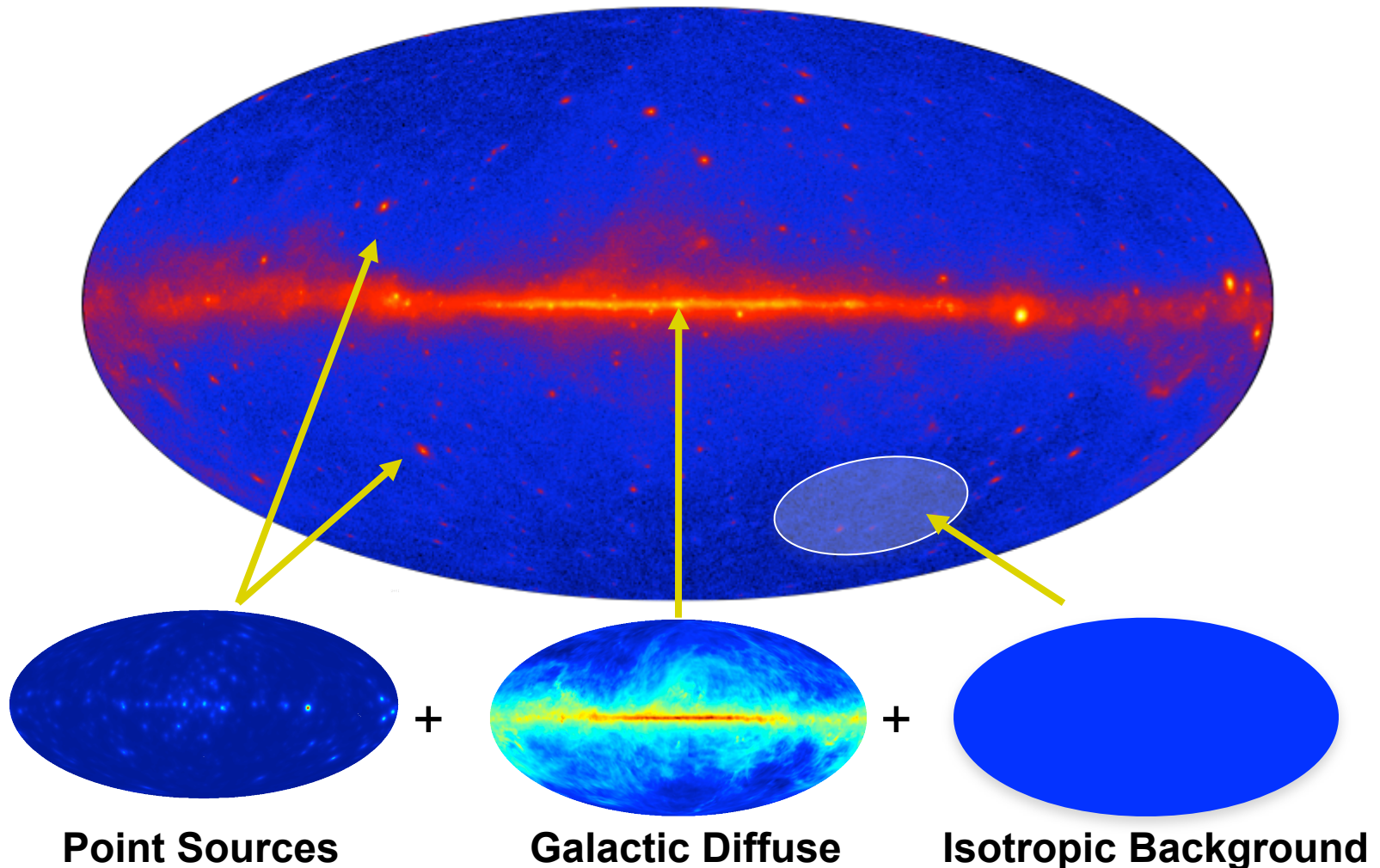
Local

Galactic

Extragalactic

LAT Data Set

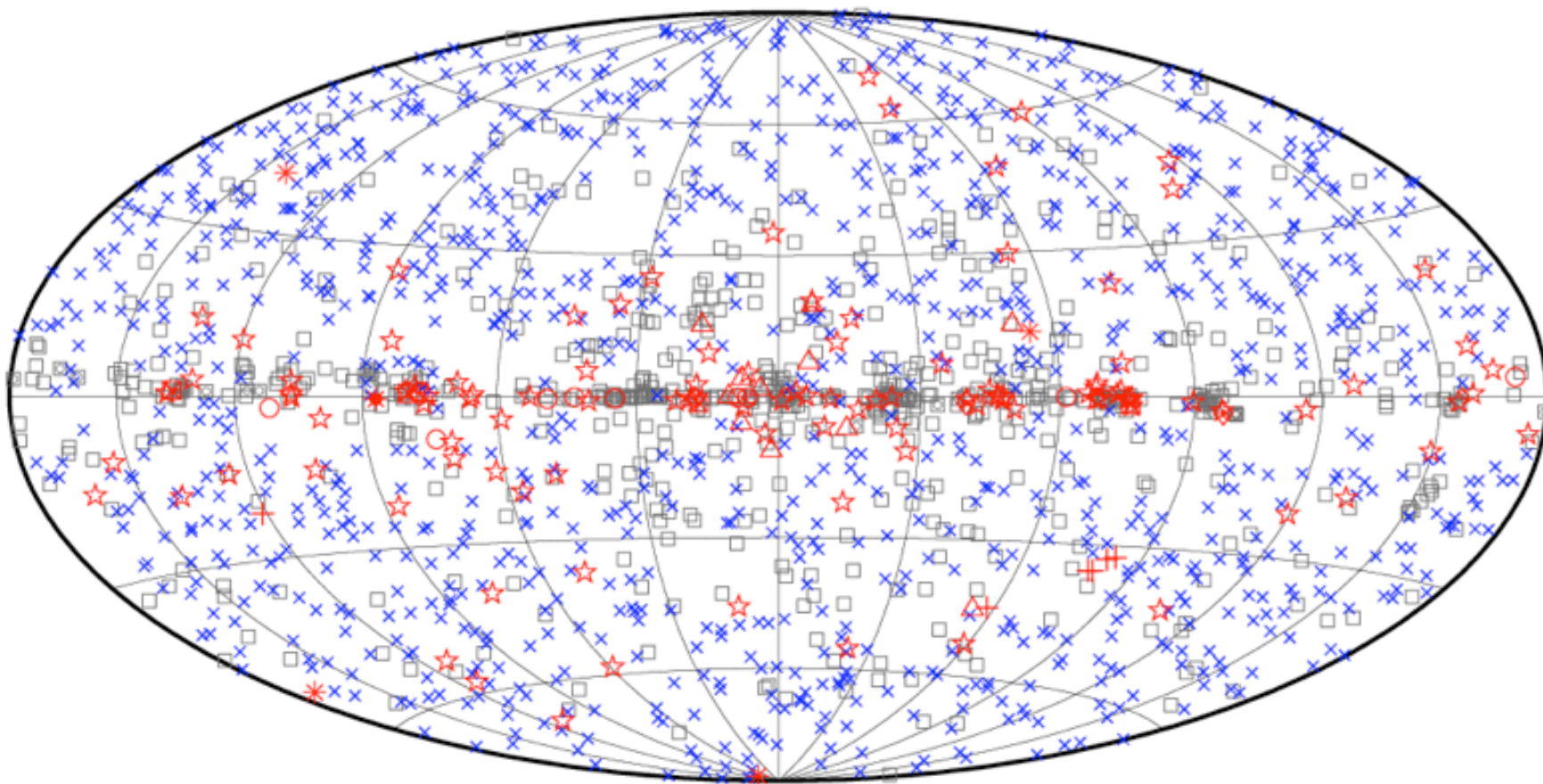
- The LAT data consists of events from numerous different astrophysical sources + multiple sources of background



Detection and Analysis of Point Sources

- Finding point sources in the LAT dataset is an iterative process
 1. Generate seed positions
 - *Easiest to use source catalog for first iteration*
 2. Simultaneously fit putative sources plus background
 3. Apply cut to remove sources that are not significant
 4. Look at residuals to find new candidate sources
 5. Iterate
- All-sky analysis is too computer-intensive
 - Requires sky be divided into “manageable” regions
 - Source extension or spectral shape can add to the complexity

Sources in the 2-year catalog

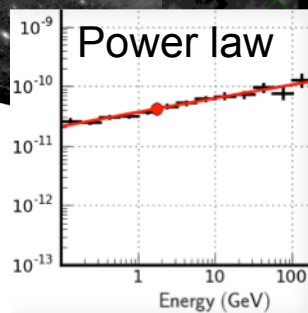


- | | | |
|------------------|--|--------------------|
| □ No association | ⊠ Possible association with SNR or PWN | |
| × AGN | ☆ Pulsar | △ Globular cluster |
| * Starburst Gal | ◇ PWN | ⊠ HMB |
| + Galaxy | ○ SNR | ★ Nova |

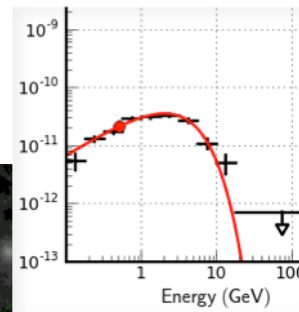
Spectral Shape

MRK 421

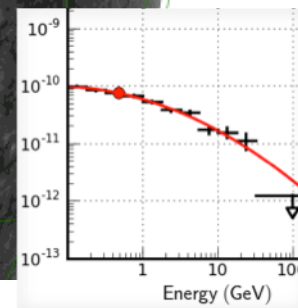
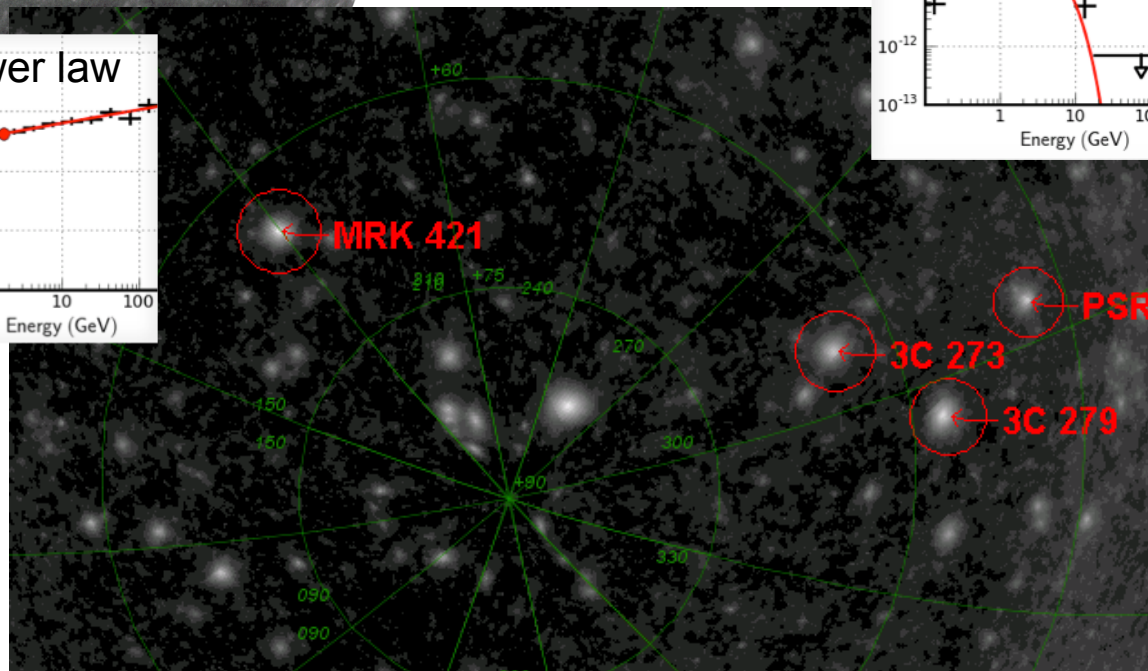
← 3C 273
← 3C 279
← PSR J1231-1411



AGN typically
show a power law
spectrum



Pulsars appear
best fit with an
exponentially
cutoff power law



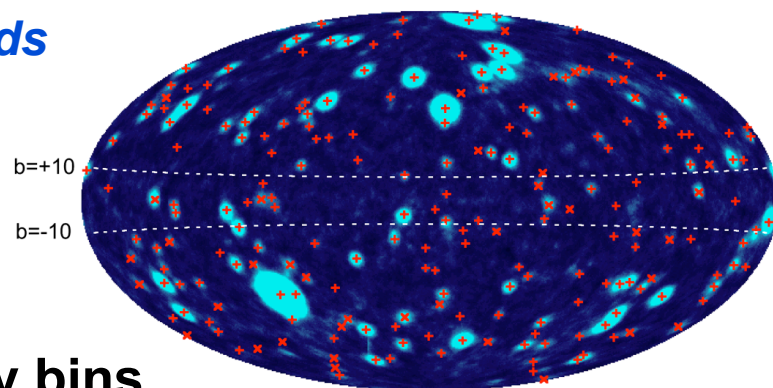
**Spectral shape is a contributing factor in whether
or not a source is significantly detected**

Use log parabola or
broken power law if
it gives a better fit

Variability

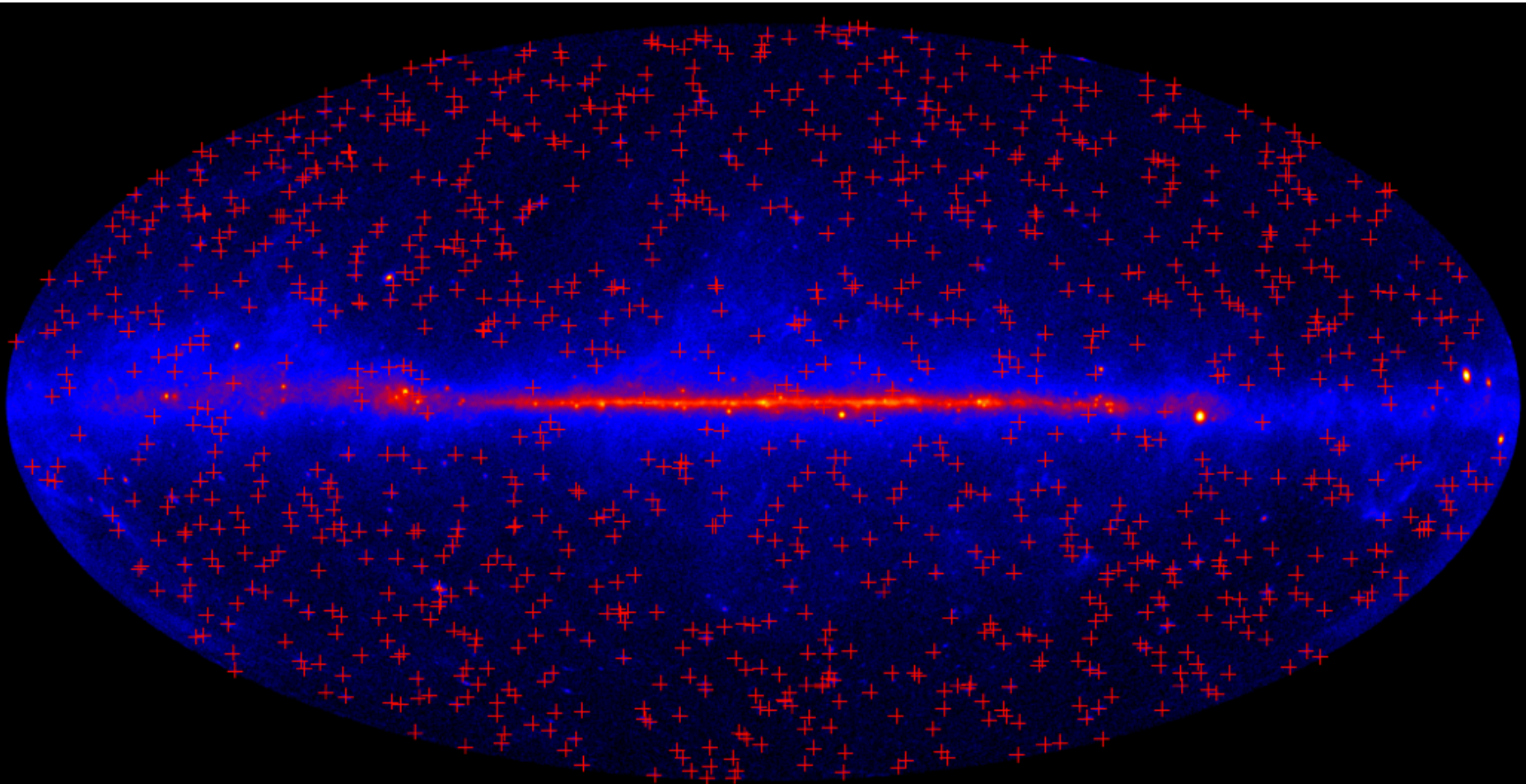
The Fermi sky is a
variable sky!

- Divide data set into time bins based on the type of variability you are looking for, and the source significance
 - Bright flares can be visible on daily timescales
 - Faint sources require more integration time
 - Avoid timescales that occur in the data, but are not intrinsic to the source
 - 93 min orbital period
 - 3.1 hour rocking profile (north+south)
 - 1 day cycle of particle backgrounds
 - 28 day lunar cycle
 - 53 day orbital precession period
 - 1 year solar cycle
- LAT point source catalogs use 30 day bins
 - May miss small amplitude short-duration flares
 - Variable source catalog available soon!



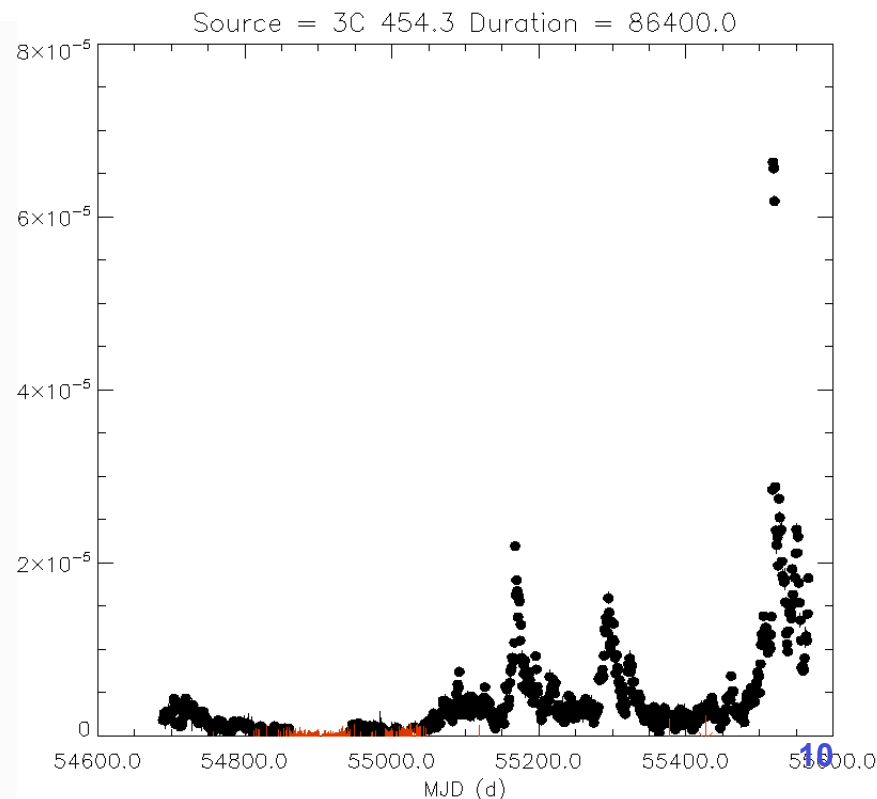
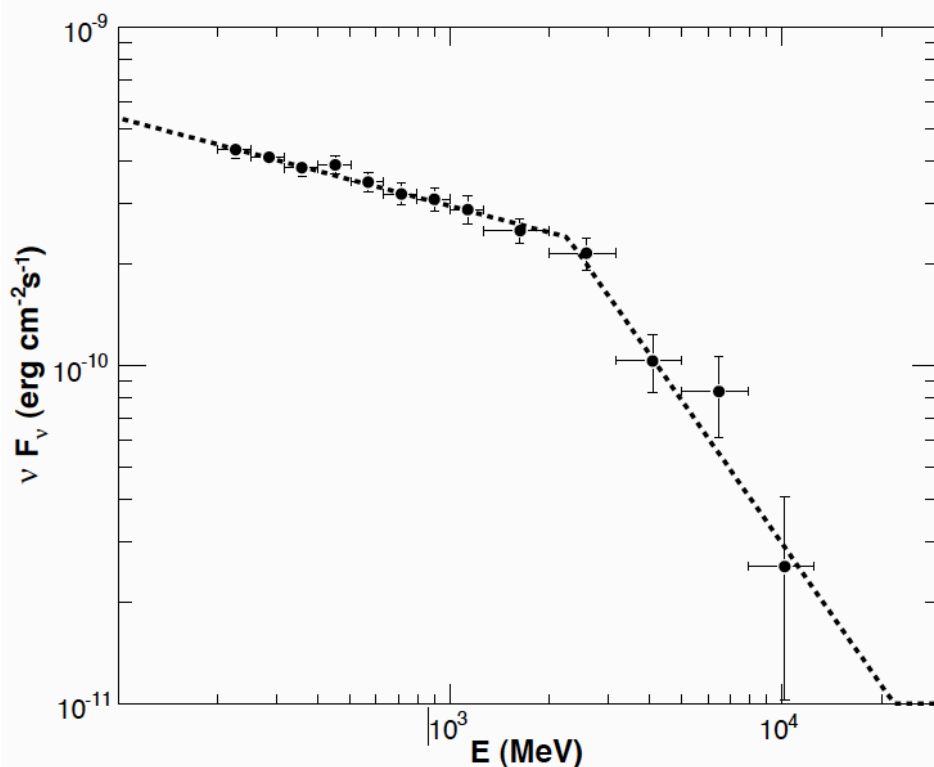
Blazars

- The most numerous class in the LAT data!



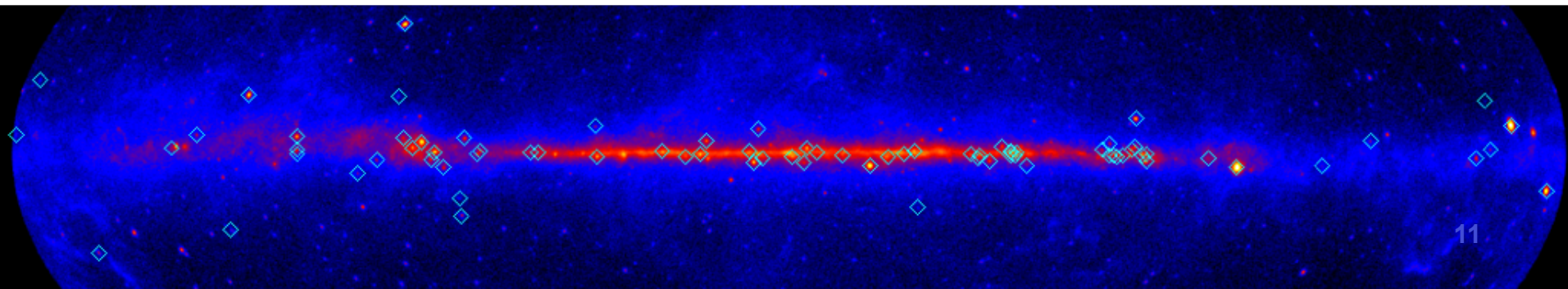
Detecting LAT Blazars

- **Blazar detectability is affected by both spectral and temporal characteristics**
 - BL Lacs and FSRQs have spectral peaks in different energy ranges (spectral index varies widely)
 - Flux varies significantly with time
 - 2nd catalog of LAT AGNs released concurrent with 2FGL



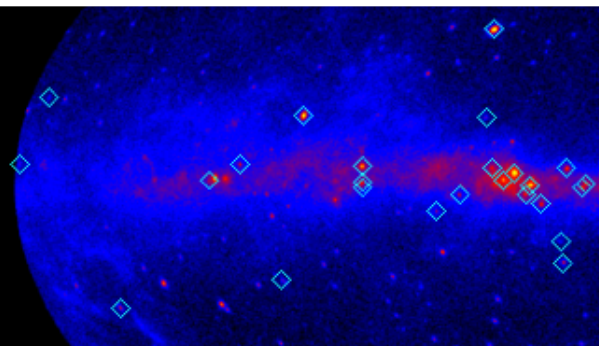
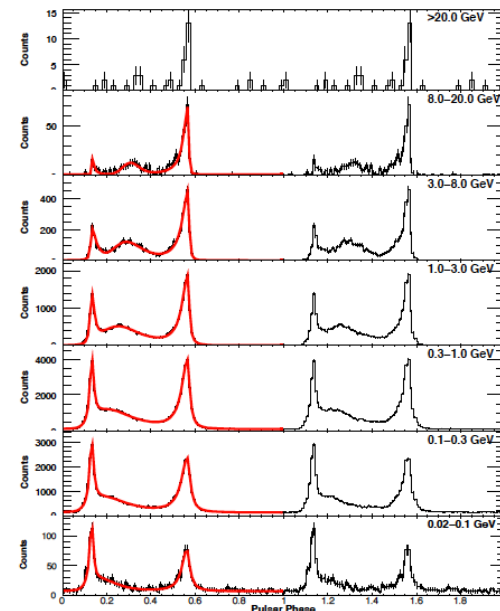
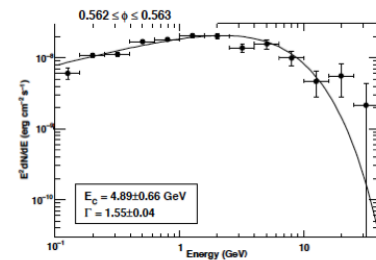
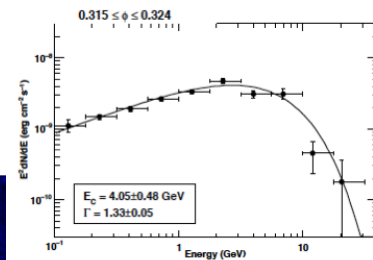
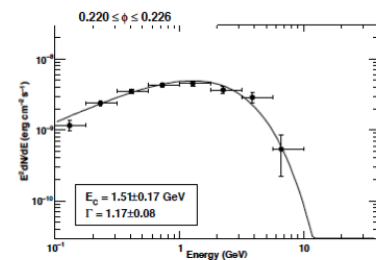
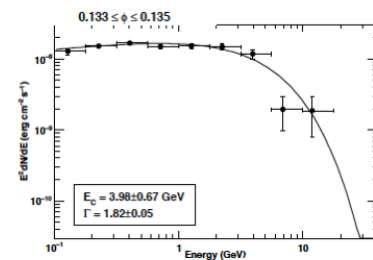
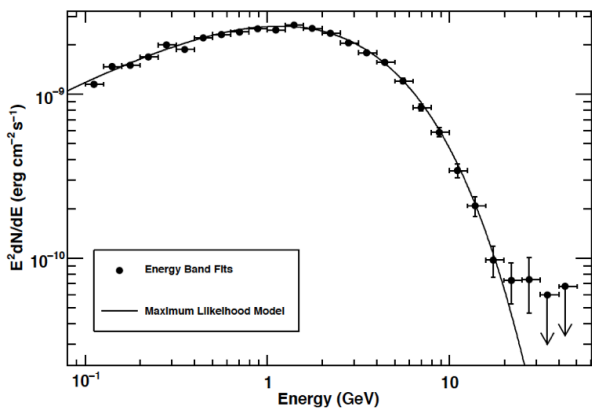
Young Pulsars

- **Highly energetic pulsars have long been known to be gamma-ray emitters**
 - Typically discovered by applying known radio ephemerides to the gamma rays
 - Can also be discovered in the gamma-ray data (26 with LAT)
 - Non-varying, with highly curved spectra



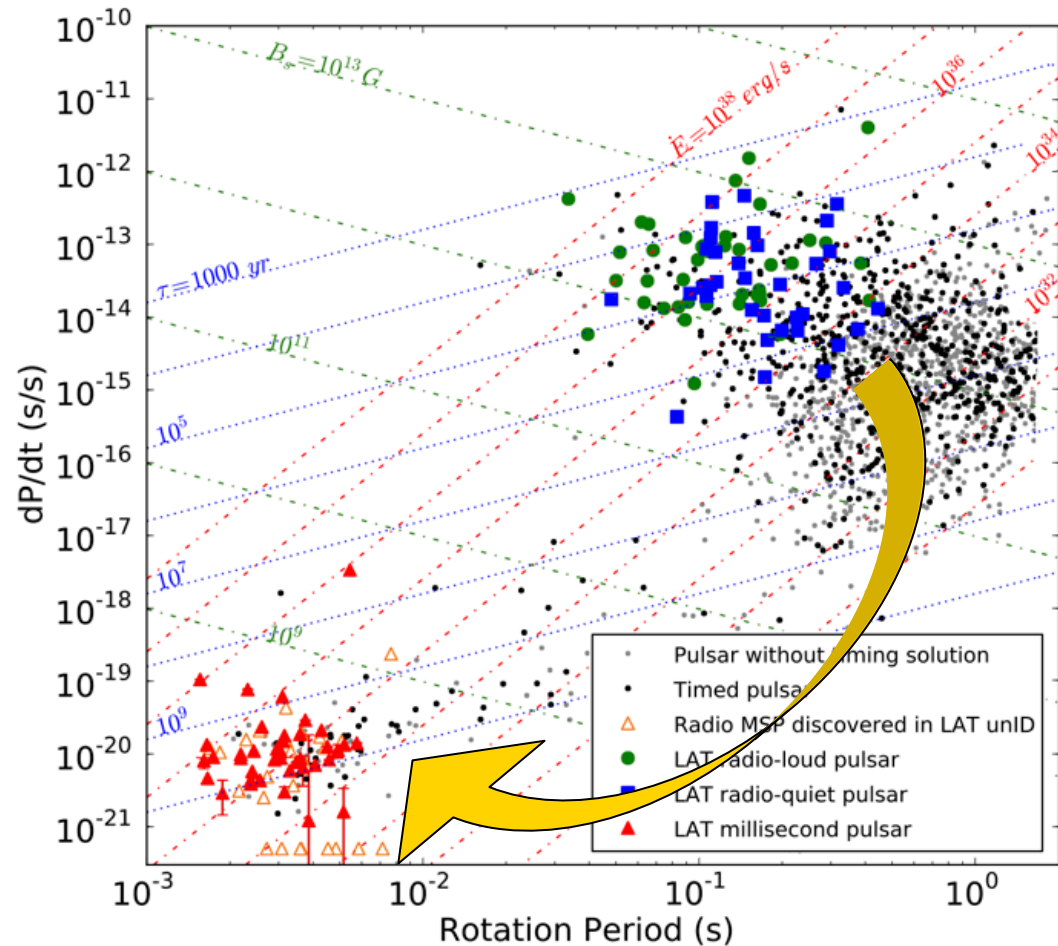
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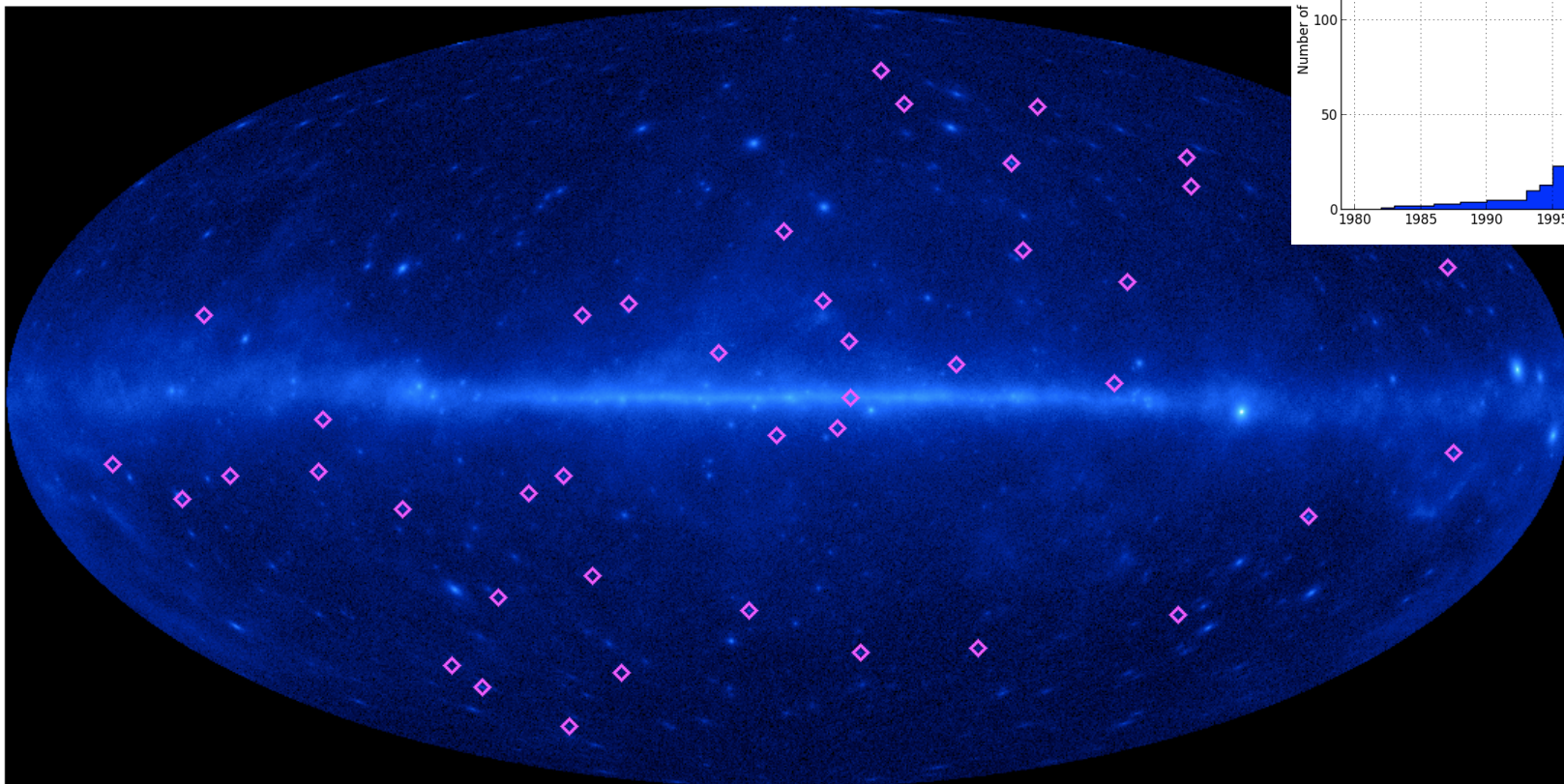
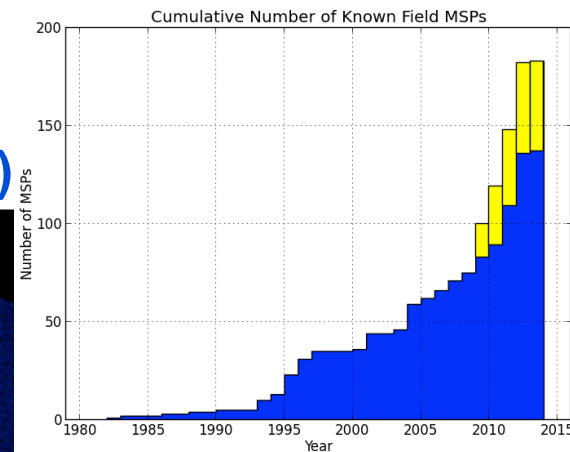
Recycled Pulsars

- Over time young energetic pulsars slow down
 - Power for pulsations comes from rotation
 - Once energetics are no longer favorable, pulsations cease
- Pulsars in binaries can get a second life through mass transfer
 - Increase in angular momentum produces millisecond periods and high energetics



Millisecond Pulsars

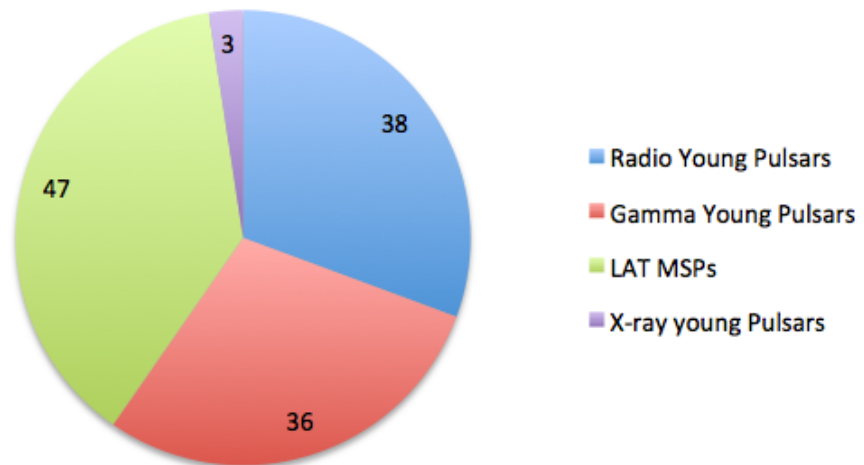
- A number of new millisecond pulsars have been found in the LAT data
 - Radio searches in non-variable LAT sources that lack counterparts
 - Significant increase in Galactic MSPs (~60 + 40 from LAT unassociated sources)



Pulsar Populations

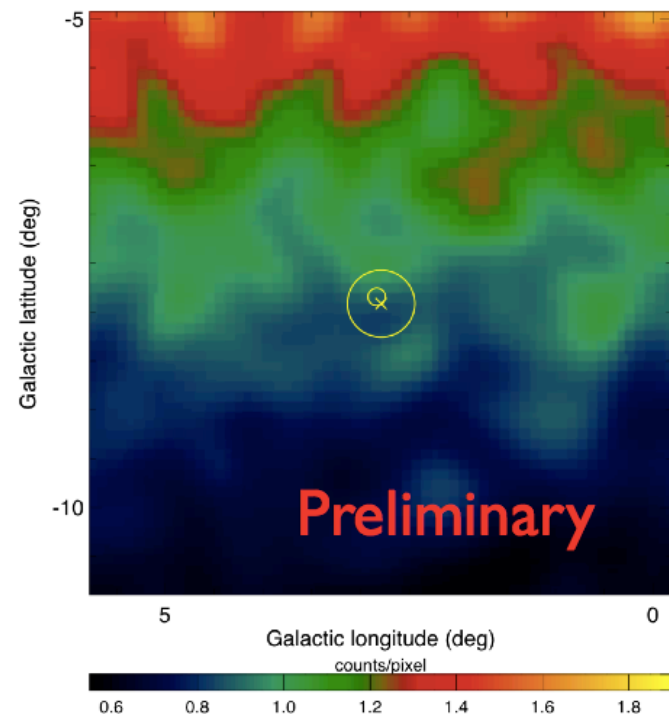
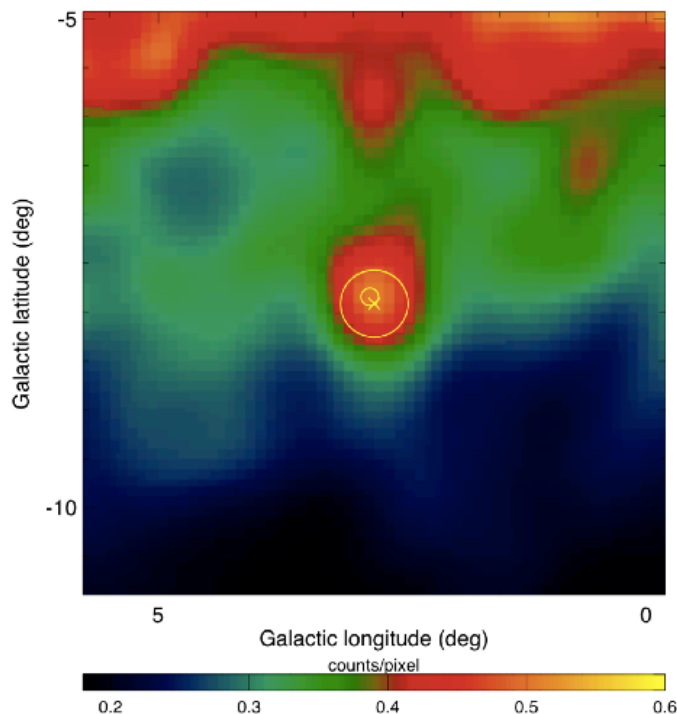
- The LAT-detected pulsars are typically referred to by their discovery method
 - Radio-selected used known radio ephemerides to find the LAT pulsations
 - Gamma-selected were discovered by folding the gamma-ray data (blind searches), and are usually radio-quiet (or very radio-faint)
 - Nearly all LAT MSPs were all found using radio ephemerides
 - *One MSP has been discovered using blind search techniques*

**Second Pulsar Catalog
just released!**
arxiv:1305.4385



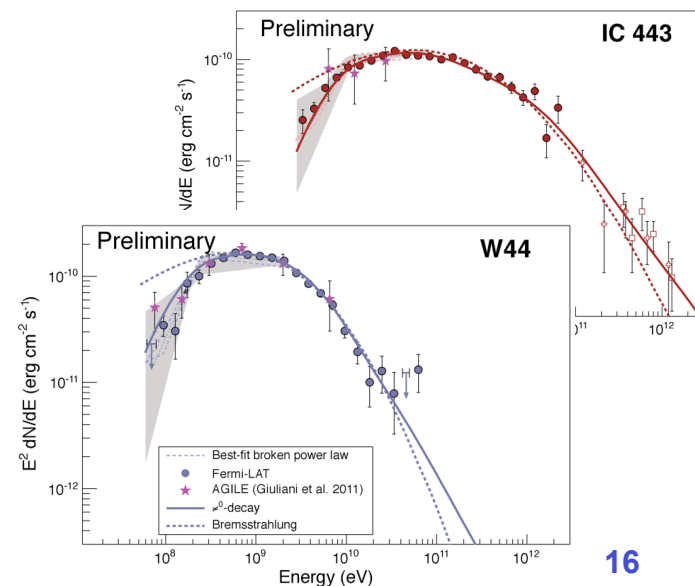
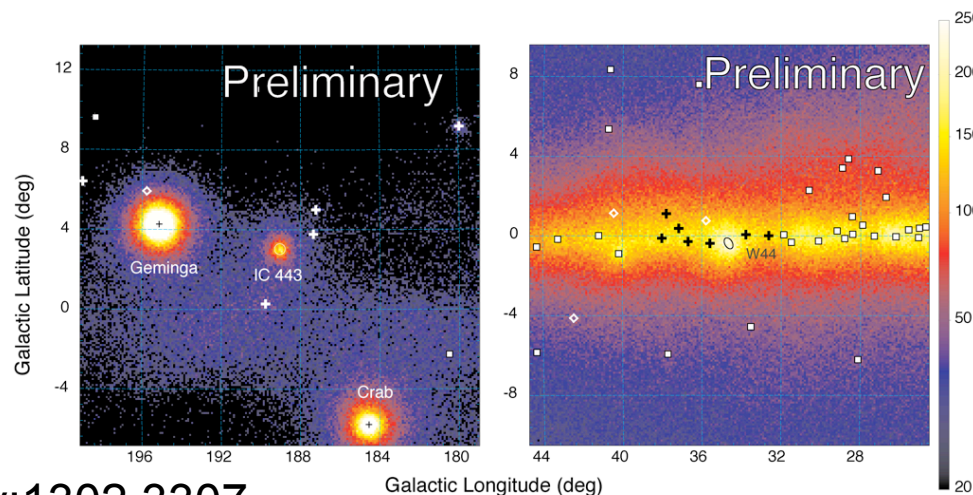
Globular Clusters

- Some globular clusters have long been known to contain numerous MSPs
 - LAT detects 11 sources coincident with globular clusters
 - In one instance (J1823-3021A) a single luminous gamma-ray pulsar has been found to be responsible for the entire LAT-detected emission from the cluster



Supernova Remnants / Pulsar Wind Nebulae

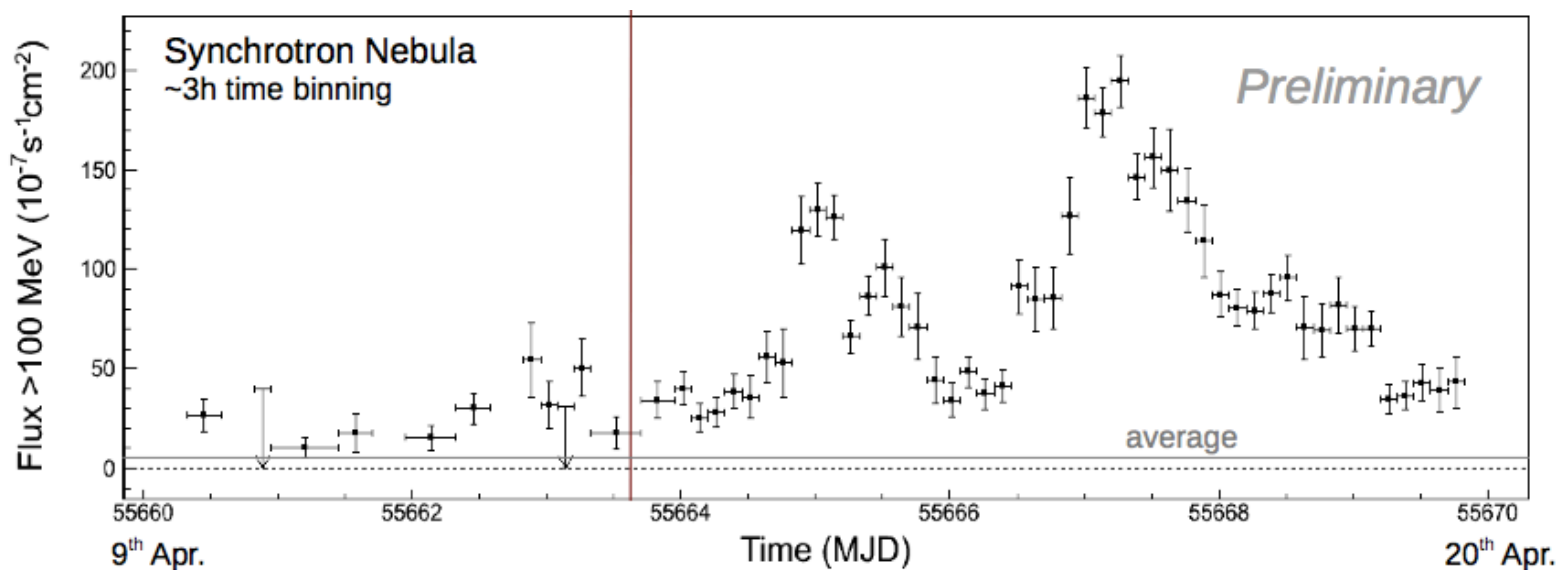
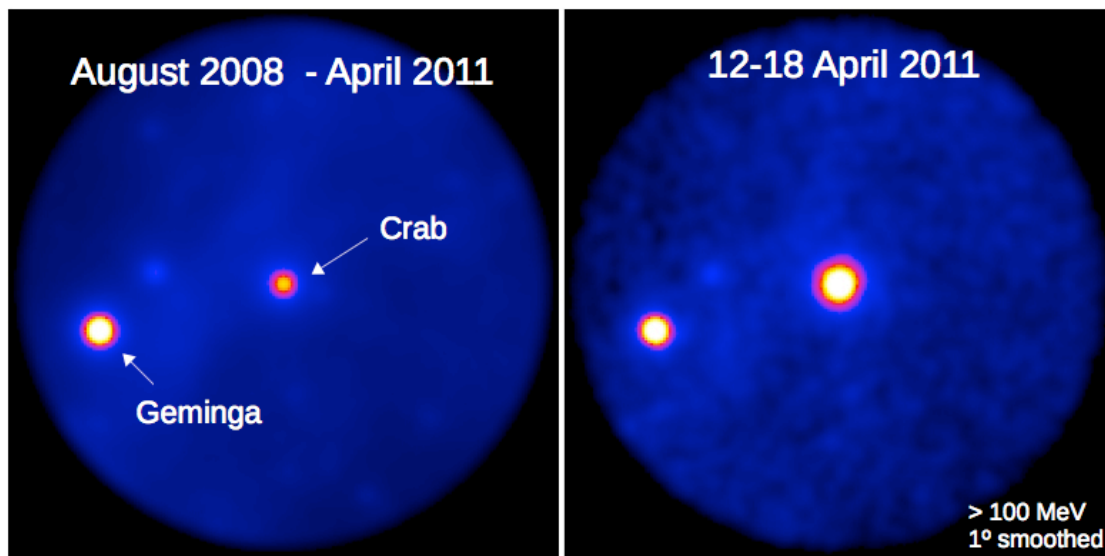
- Third most numerous known source class behind blazars and pulsars
 - 2FGL has ~65 SNRs/PWNe associations in a very narrow distribution along the galactic ridge
 - Some positively identified by matching their extension to that in other wavebands
 - *Compare result of analysis with extended spatial templates to point source hypothesis*
 - Paper on search for PWN available ([arxiv:1011.2076](https://arxiv.org/abs/1011.2076))
 - SNR Catalog in development



The Variable Crab!

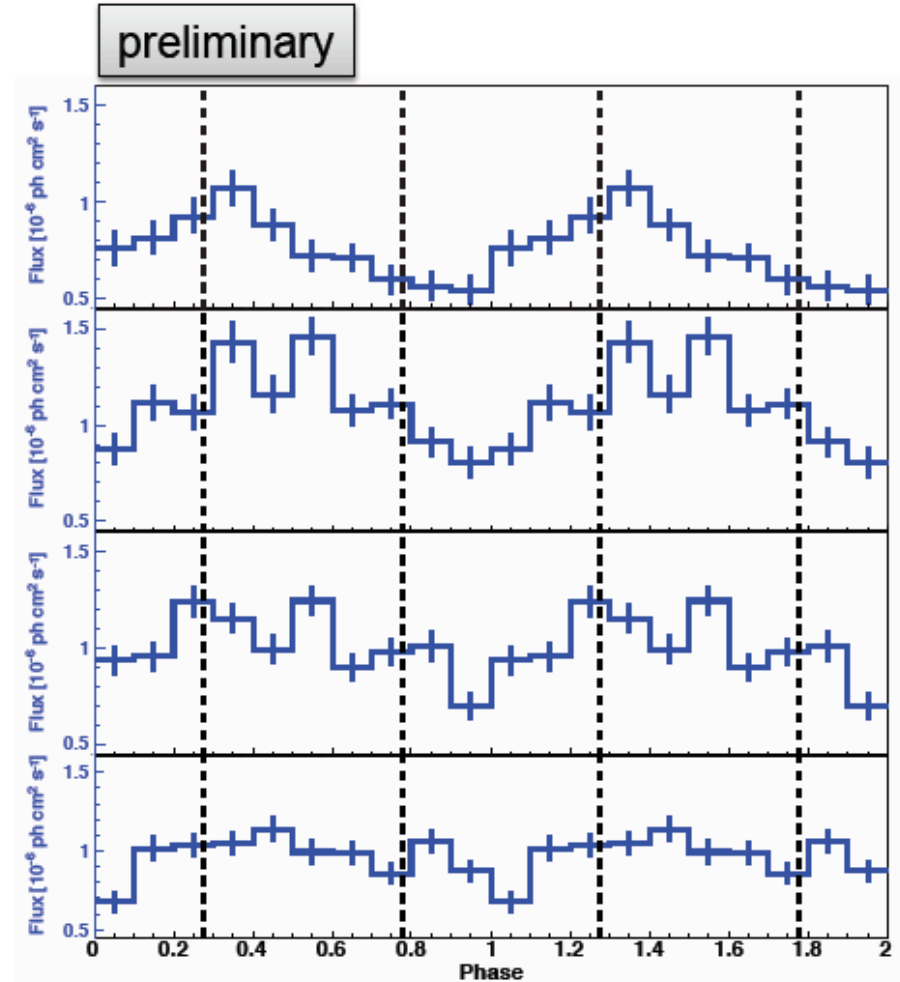
- The Crab pulsar + SNR is used as a calibration source in high-energy astronomy

Variability from the
nebular component
was quite a surprise!



Other Galactic Sources

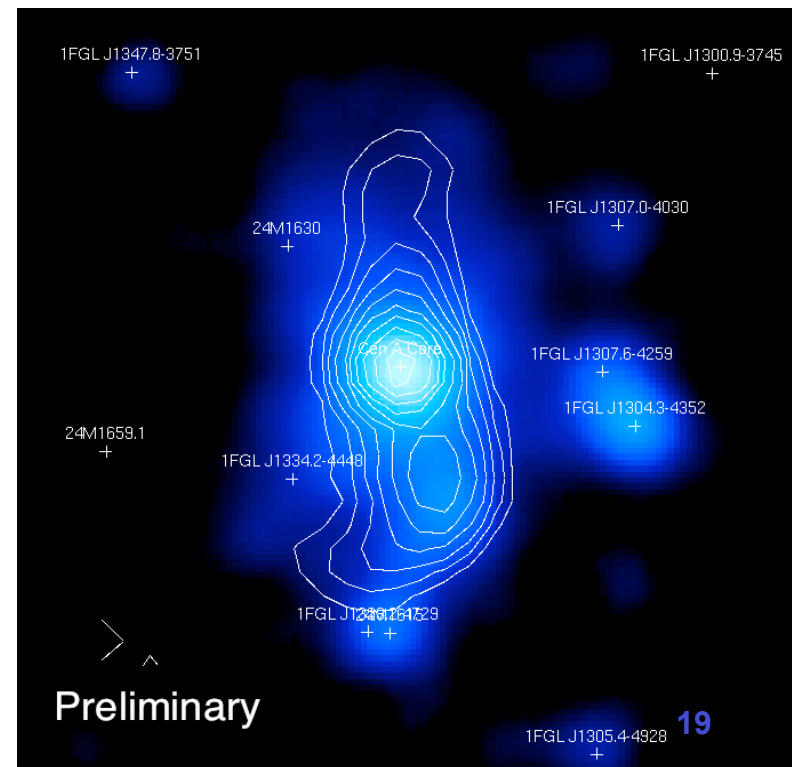
- The LAT detects periodic signals from four HMXBs:
 - Cyg X-3
 - LS 5039
 - LSI +61 303
 - *LSI +61 303 orbital signal appears to have slowly disappeared since the beginning of the mission*
 - 1FGL 1018.6-5856
- Eta Carina is also detected.
The only colliding wind binary seen by the LAT



Folded light curve in 6-month intervals

Other Extragalactic Sources

- **Narrow-Line Seyfert 1s**
 - Six of these sources have been associated with LAT emission
- **Starburst Galaxies**
 - 2FGL had 4 starburst galaxy associations
 - *Similar mechanism to Eta Carina?*
- **Radio Galaxies**
 - 12 radio galaxy associations (including M87, NGC 1275, Fornax A, and IC 310)
 - Centaurus A radio lobes are fully resolved by the LAT

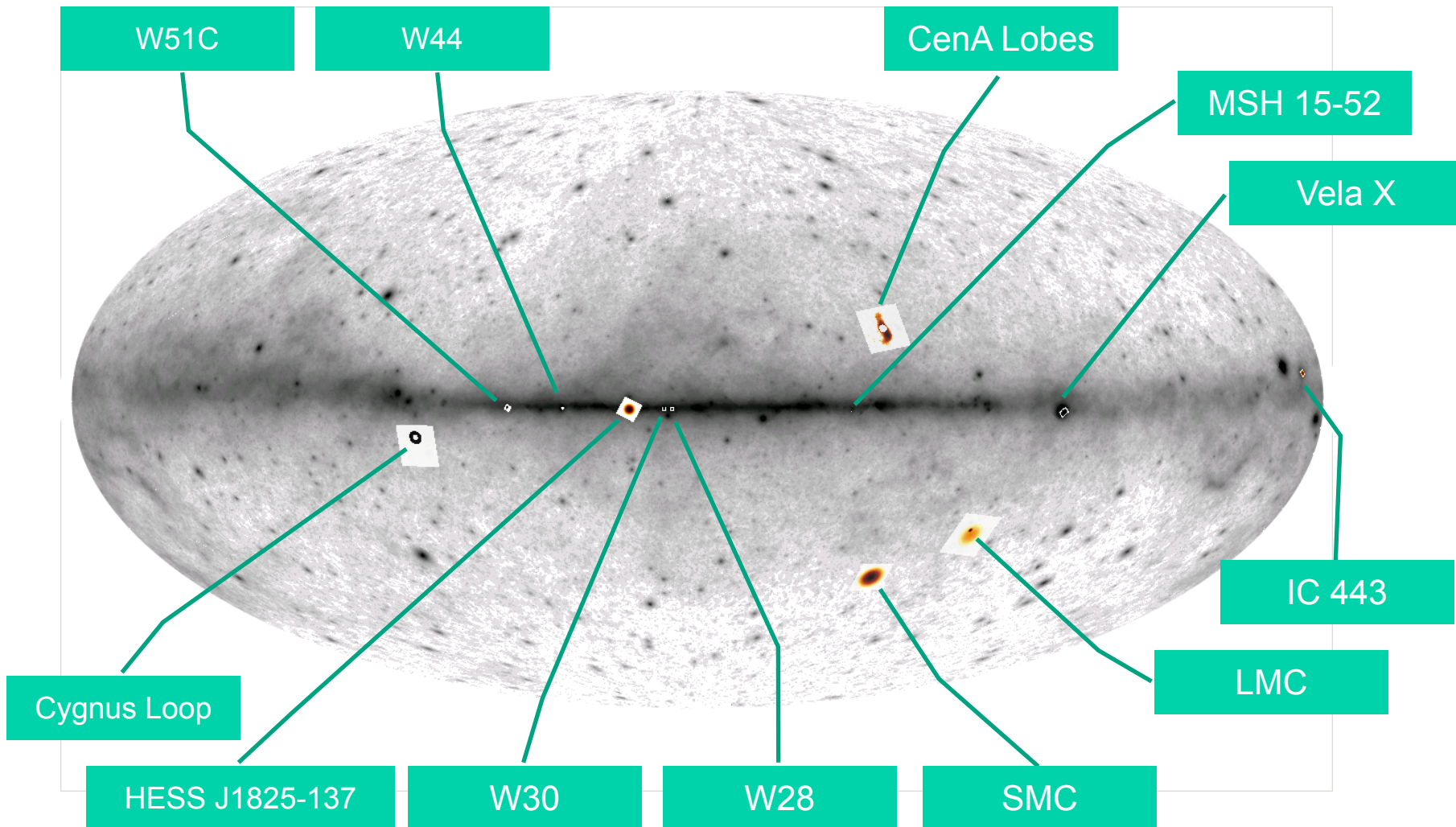


Spatially Extended Sources in 2FGL

Extended Source	Spatial Form	Spectral Form
SMC	2D Gaussian	Exp Cutoff PL
LMC	2D Gaussian ^a	Exp Cutoff PL
IC 443	2D Gaussian	Log Parabola
Vela X	Disk	Power Law
Centaurus A (lobes)	Contour Map	Power Law
MSH 15–52	Disk	Power Law
W28	Disk	Log Parabola
W30	Disk	Log Parabola
HESS J1825–137	2D Gaussian	Power Law
W44	Ring	Log Parabola
W51C	Disk	Log Parabola
Cygnus Loop	Ring	Exp Cutoff PL

Longer data sets will have more extended sources

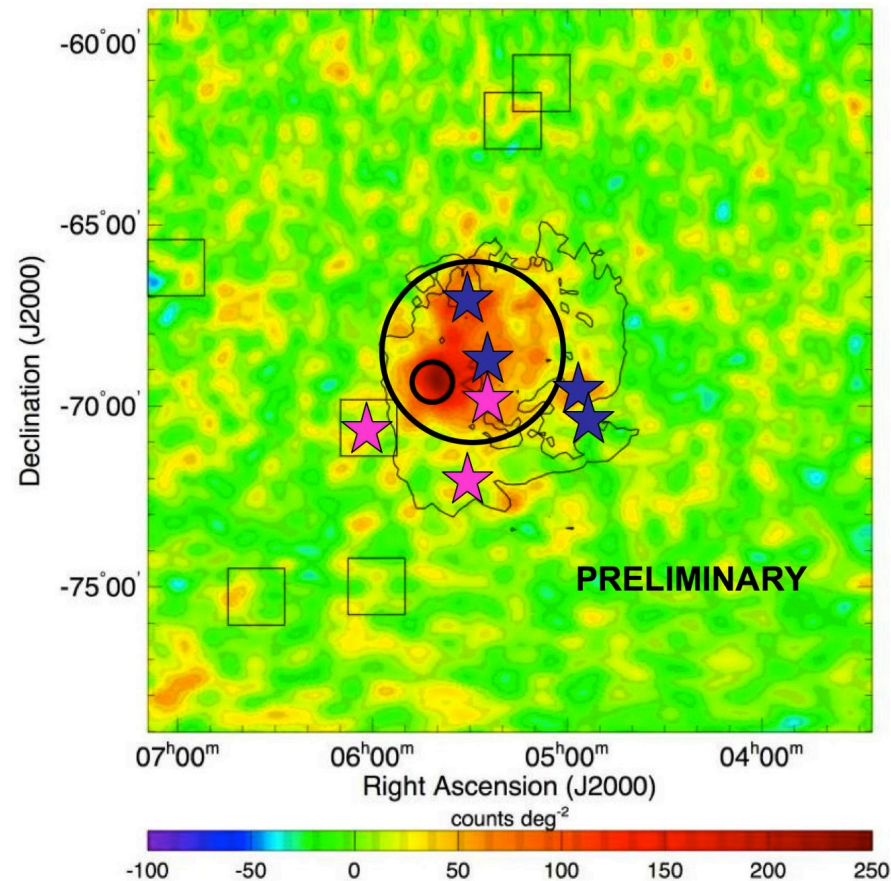
Extended Source Templates



Spatial templates available on your USB drive

Extended Source Uncertainties

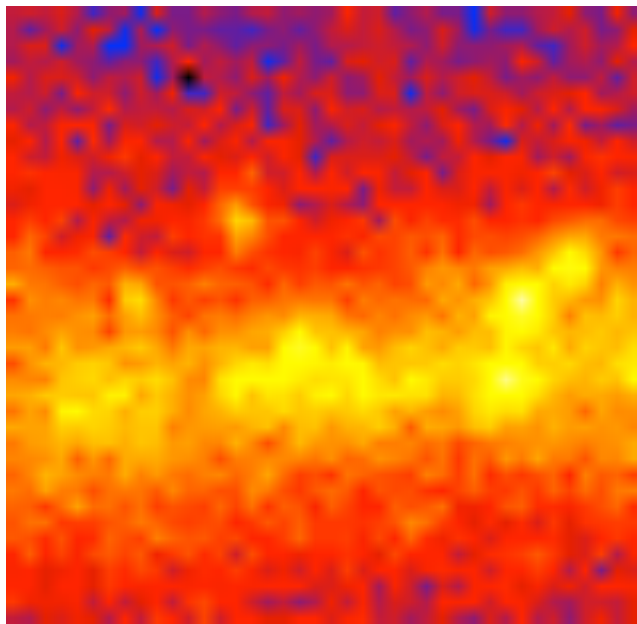
- The templates for sources that are spatially extended are approximations based on our best current knowledge
 - Analysis of regions around such sources can leave residuals that look like point sources
 - For example, there are several point sources in the vicinity of the Large Magellanic Cloud. One of these has a blazar counterpart, but several do not and could be artifacts
 - You can test for spatial extension by comparing results for different templates



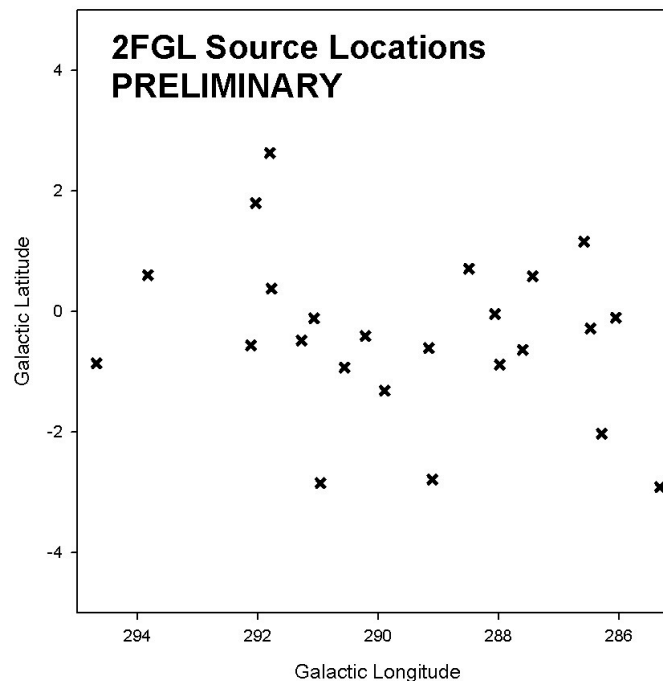
LAT LMC map with overlay showing 2 component template and nearby sources

Source Confusion

- There is a concentration of sources at low Galactic latitudes toward the inner Galaxy
 - This results in sources close enough to each other that their Point Spread Functions (PSFs) overlap
 - Particularly significant at lower energies, so affects soft sources more
- Parts of the sky away from the Galactic Plane show little impact

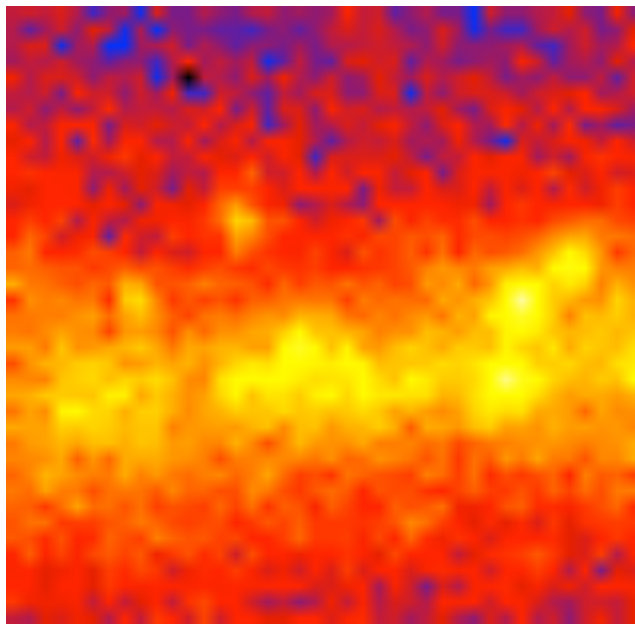


Counts map $E > 1$ GeV

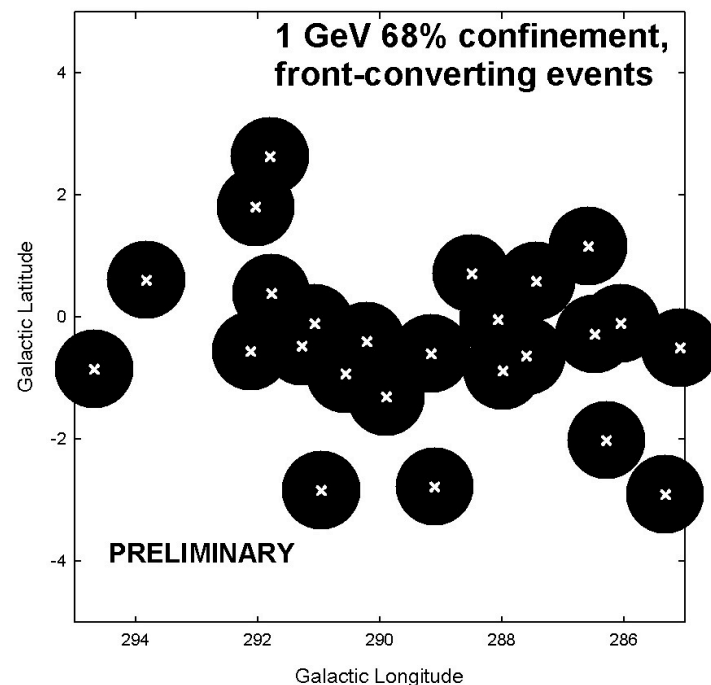


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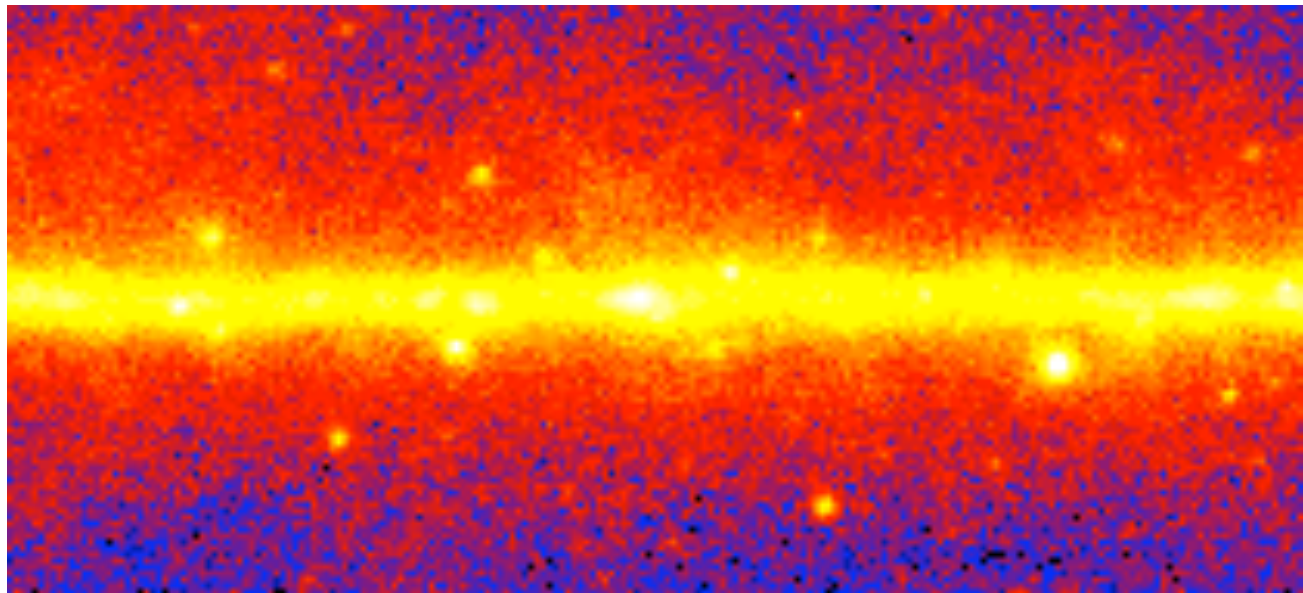
Source Confusion

- There are many sources in the Galactic Center region
 - Many overlapping PSFs
 - Lots of soft-spectrum sources
 - The diffuse model shows some residuals compared to the large-scale diffuse emission observed in this region
- LAT catalog results for the region around the Galactic Center should be considered a good first approximation rather than a comprehensive analysis.

50° x 25°

E>1GeV

2 years



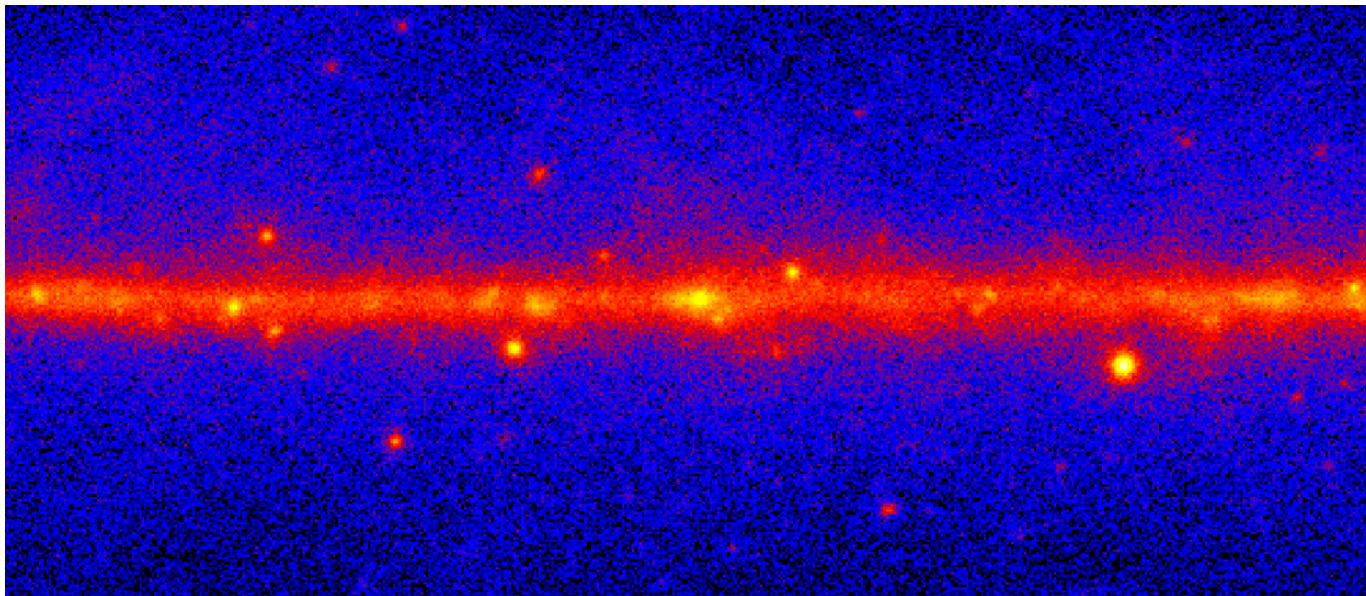
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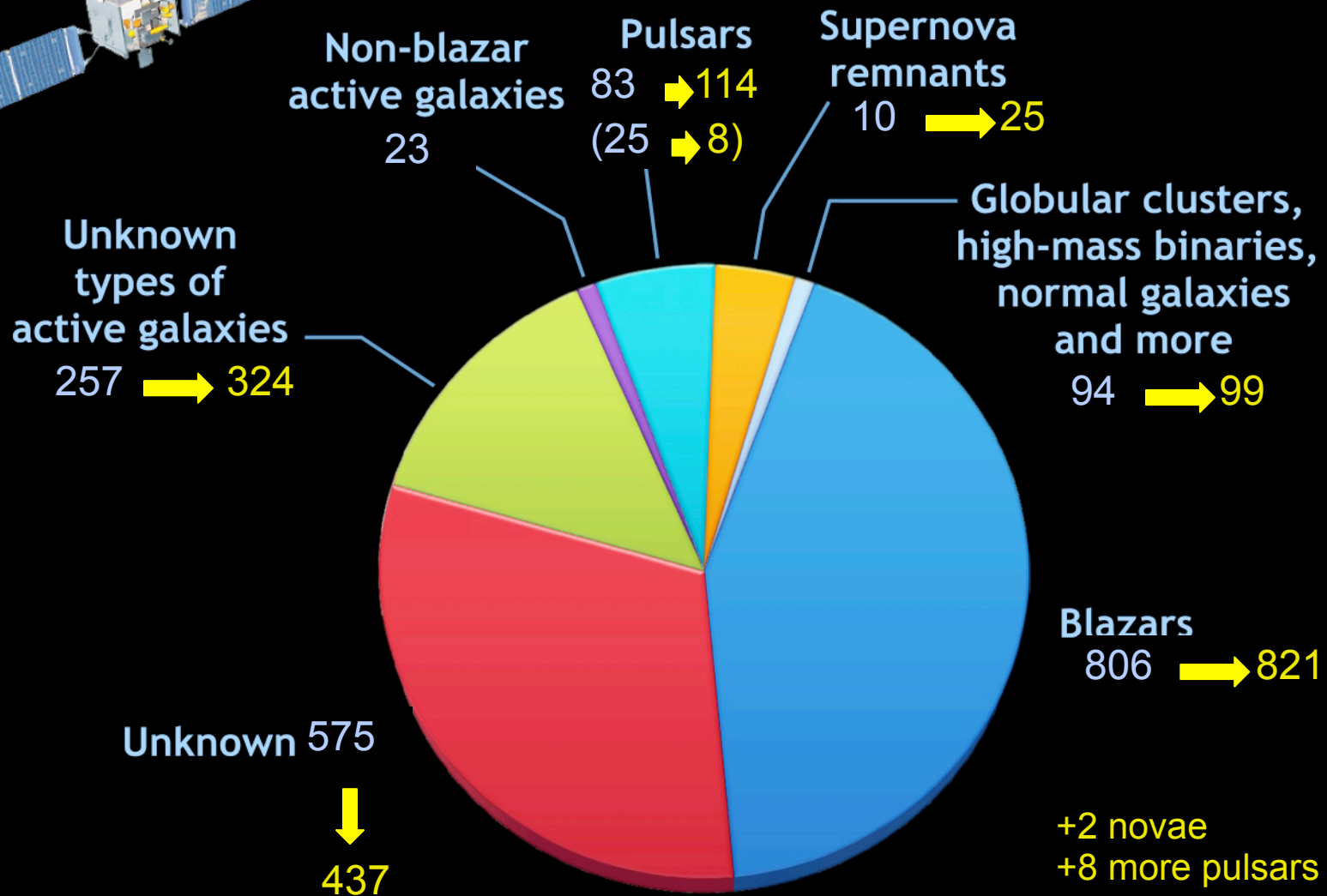
E>1GeV

4 years



What has Fermi found: The LAT two-year catalog?

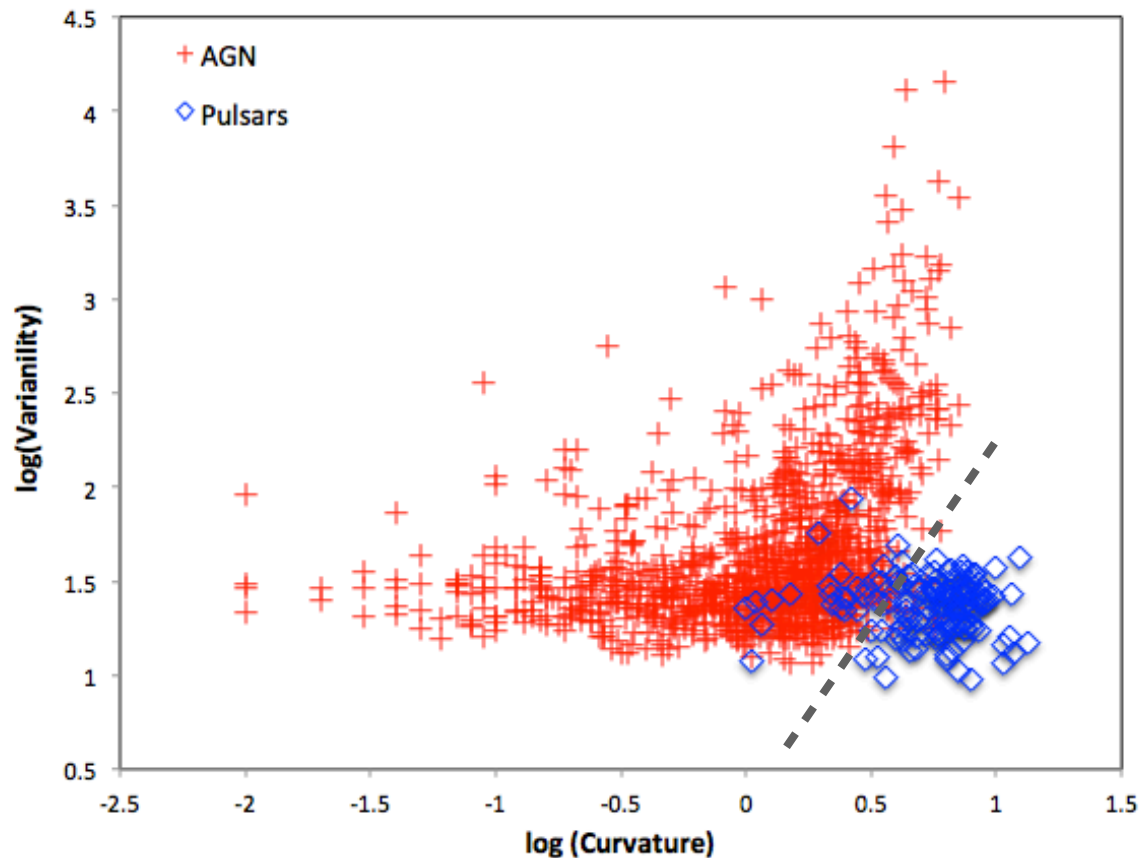
since



Credit: NASA/Goddard Space Flight Center

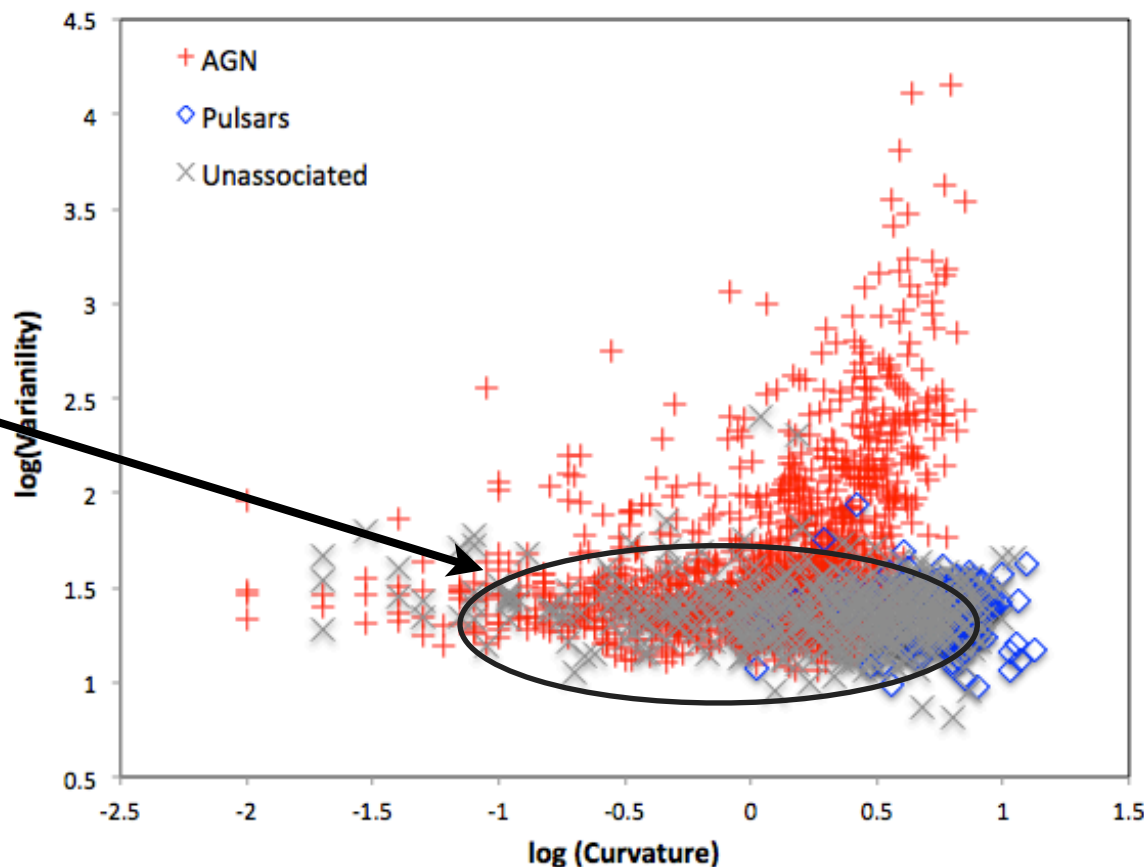
Investigating the Unassoccs

- Compare the gamma-ray unassociated sources with known gamma-ray classes
 - Only AGN and pulsars are numerous enough for statistical analyses



Investigating the Unassoccs

- Compare the gamma-ray unassociated sources with known gamma-ray classes
 - Only AGN and pulsars are numerous enough for statistical analyses



Everything
clumps
together

Challenge:
How to separate
the source types

arxiv: [1108.1202](https://arxiv.org/abs/1108.1202)

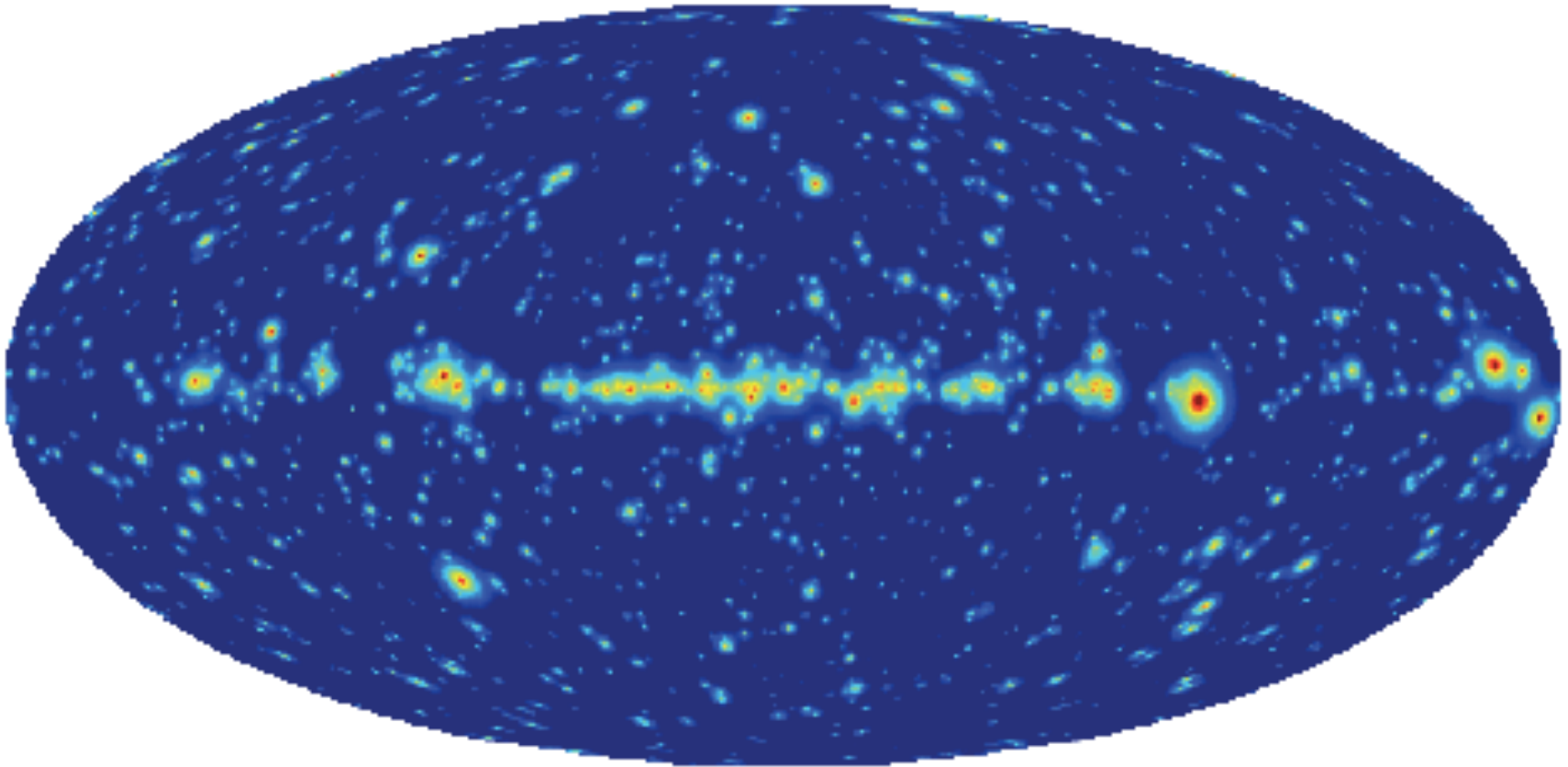
What Doesn't the LAT See?

- **Normal Seyfert Galaxies**
 - They're AGN, why aren't they seen?
- **Galaxy Clusters**
 - Filled with great targets for cosmic rays, why aren't they seen?
- **Accreting X-ray Pulsars, Magnetars**
 - Seen by GBM, extreme physics, why aren't they seen?

Is that all we see?

- The persistent point sources comprise only a subset of the data

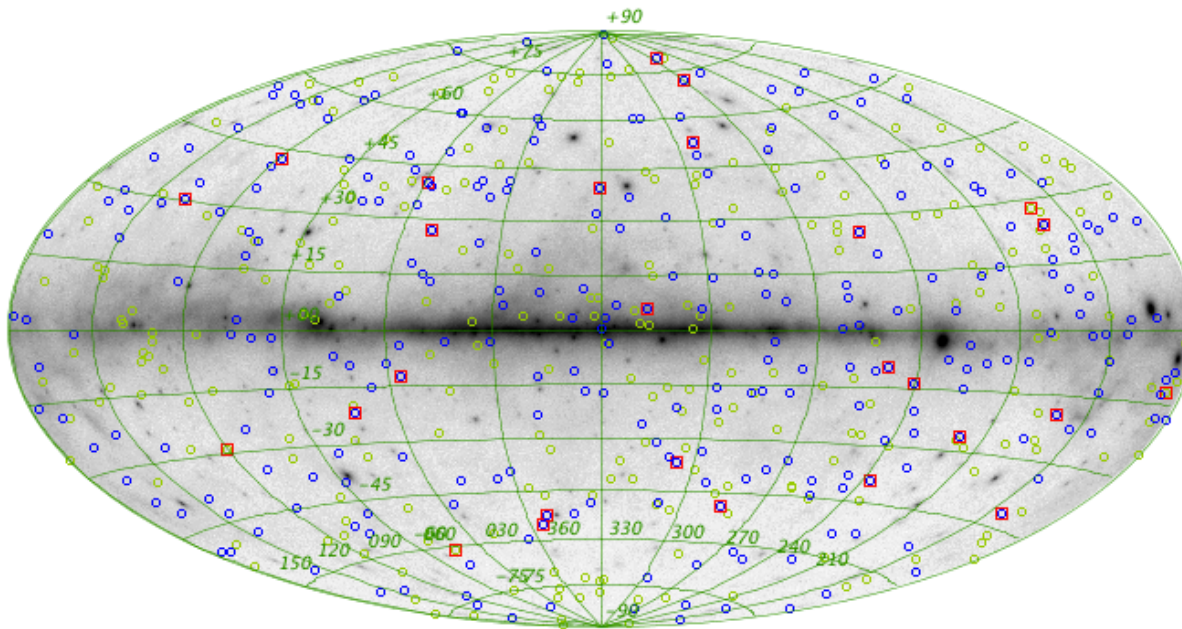
Sources, 2FGL early version



The Fermi sky is a variable sky!

Transient Events - 1

- **Extragalactic Transients: Gamma-Ray Bursts (GRBs)**
 - Rapid, very energetic events at extreme distances
 - Very short timescales (seconds to 100s of seconds)
 - Seen frequently by GBM (>1100)
 - A subset of these are seen by the LAT (~55)
 - *Must have a high-energy component*
 - *Must be within the LAT field of view (FOV)*
 - Can affect analysis if near the source of interest



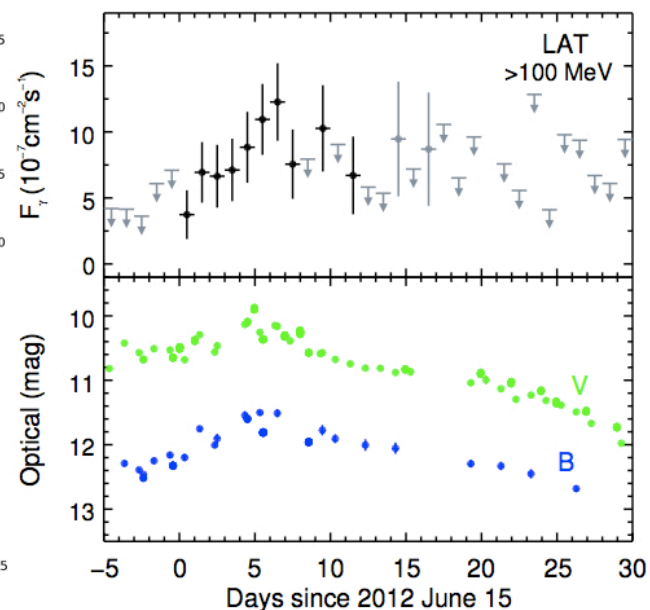
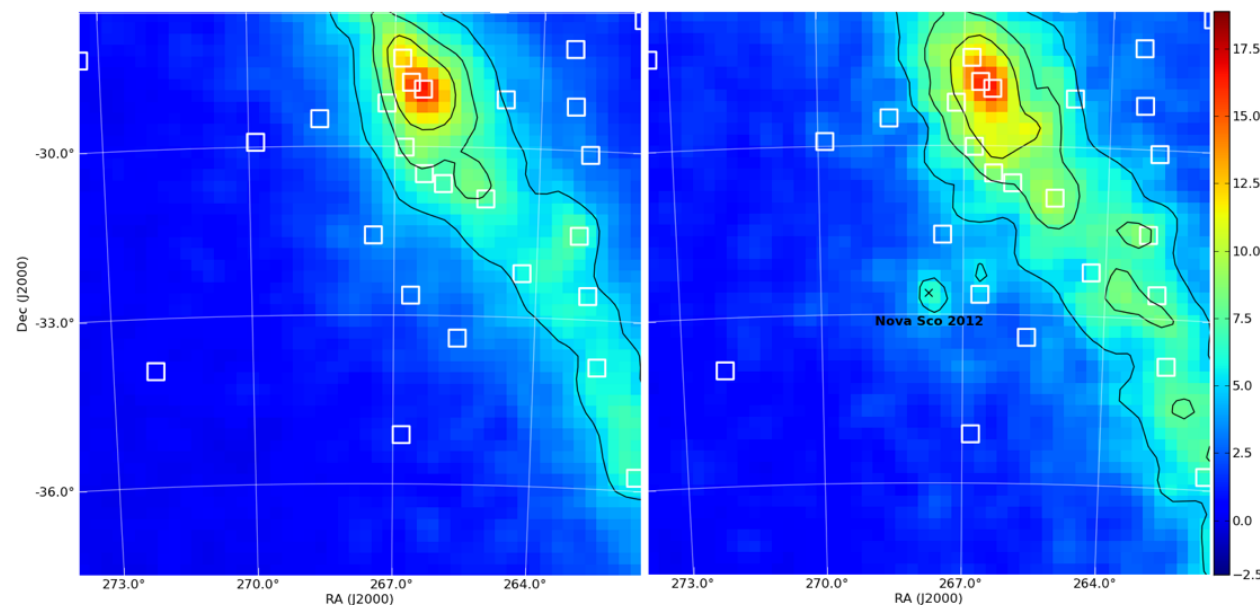
Circles:
 In Field-of-view of
 LAT ($<70^\circ$): 275
 Out of the FOV
 Squares:
 LAT detections

arxiv:1303.2908

Transient Events - 2

- Galactic Transients:

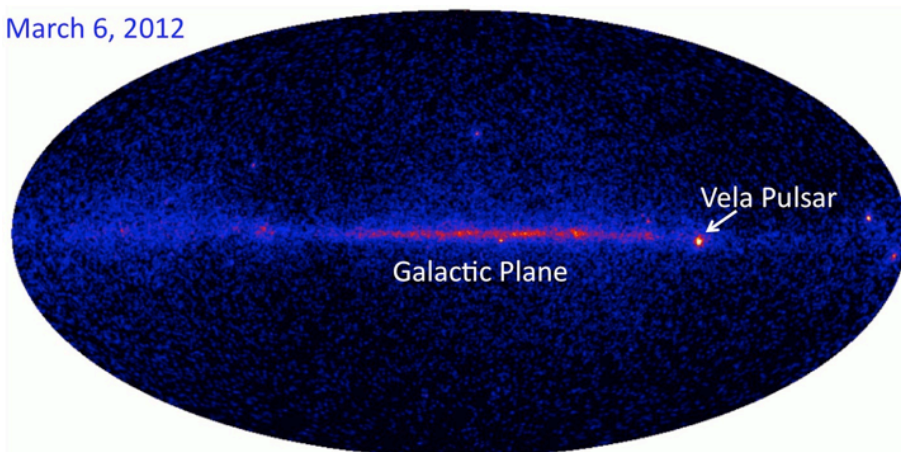
- Several Galactic transients have been seen by the LAT since Fermi started science operations
 - May be flares by background AGN*
- Three galactic novae detected by the LAT
 - Material accreting onto white dwarf explodes into surrounding medium*
 - Creates a shock front that generates gammas*
 - Medium may be dust in the system, or companion star, or...?*



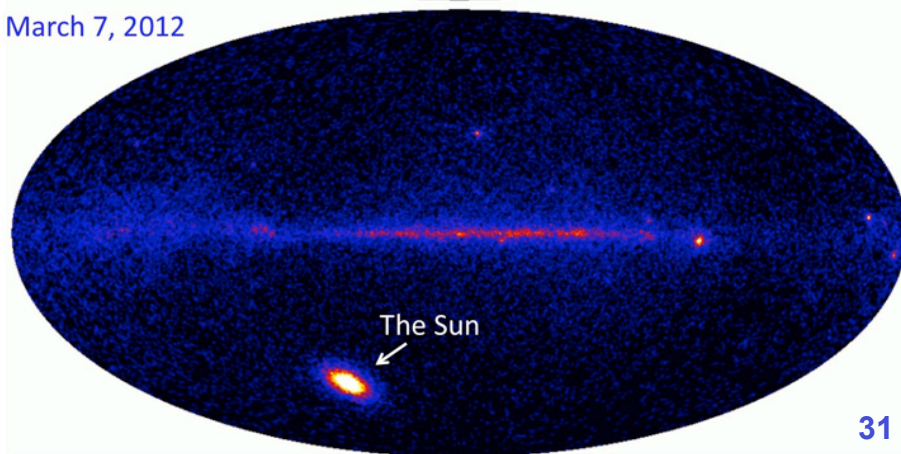
Transient Events - 3

- Some events affect the ability of the instrument to acquire data
 - In general, these events will be filtered out by the event classification process
 - Use the recommended data cuts to eliminate undesired effects
- Solar Flares
 - Last for many minutes to hours
 - Very visible in the GBM
 - Can interfere with LAT instrument response
 - Marked as “*bad*” in the data
 - As the Sun is a moving source, it can affect many other sources
 - Crab
 - 3C 279, 3C 273
 - Any other source on the ecliptic

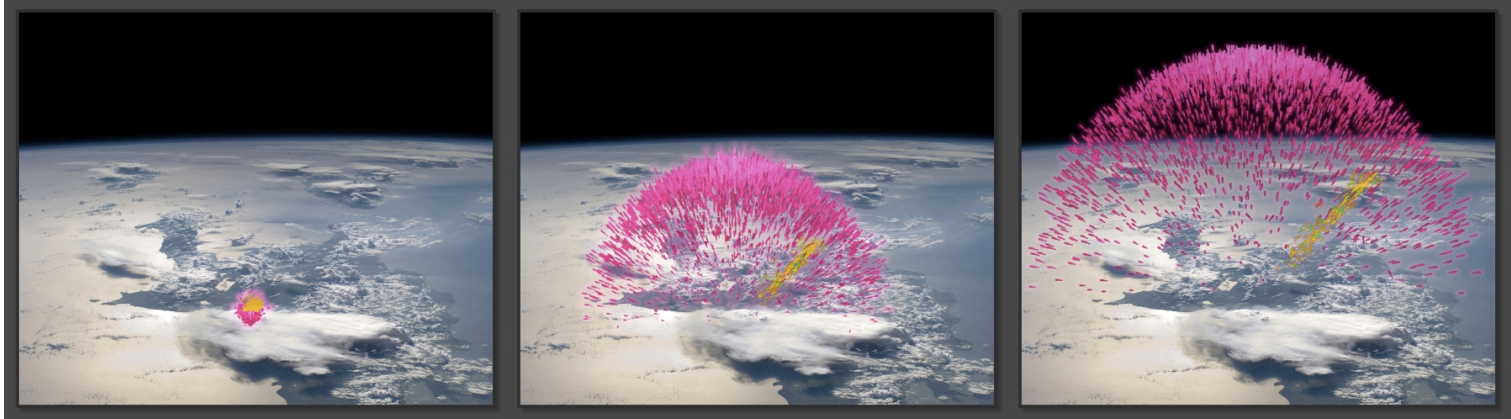
March 6, 2012



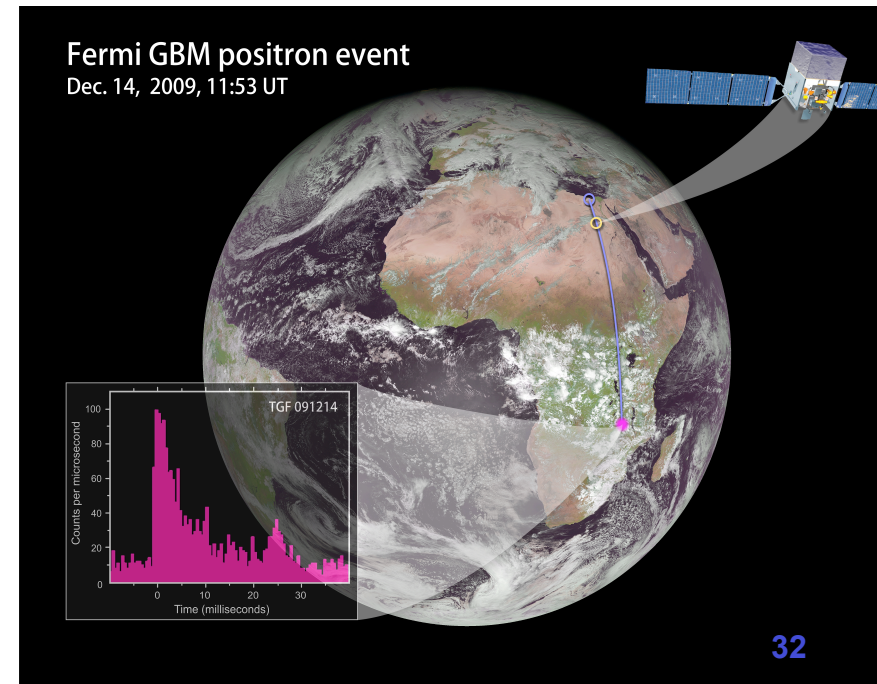
March 7, 2012



Terrestrial Gamma-ray Flashes

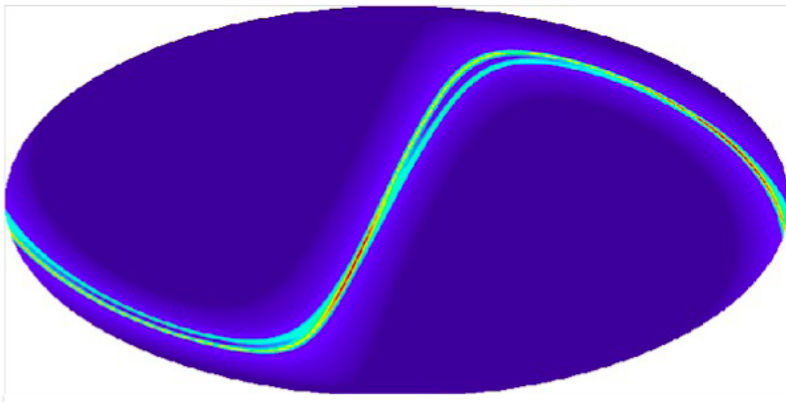


- **Terrestrial Gamma-Ray Flashes (TGFs)**
 - Several-microsecond events associated with thunderstorms on the Earth
 - Two types seen by GBM
 - *Bursts of gamma-rays from sub-satellite thunderstorms*
 - *Positron annihilation from magnetically connected thunderstorms*

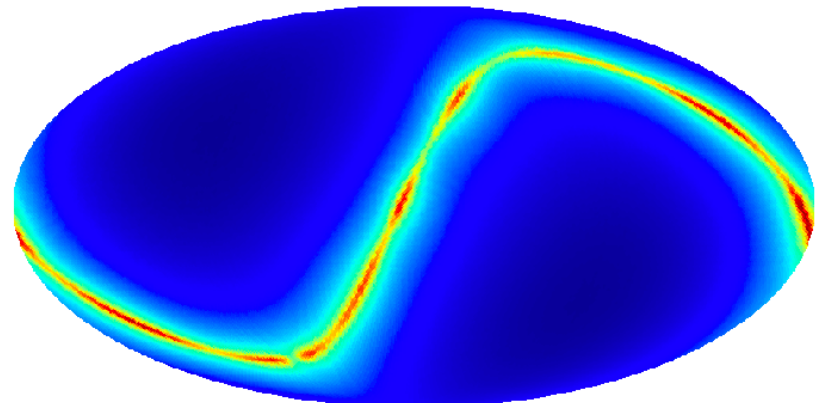


Solar System sources

- Both quiescent Sun and Moon can be seen in the 4-year integrated data set
 - LAT team is developing tools to calculate exposure-corrected templates using measured spectra
 - Sun and Moon templates will be included as an all-sky source in the next catalog analysis to be released



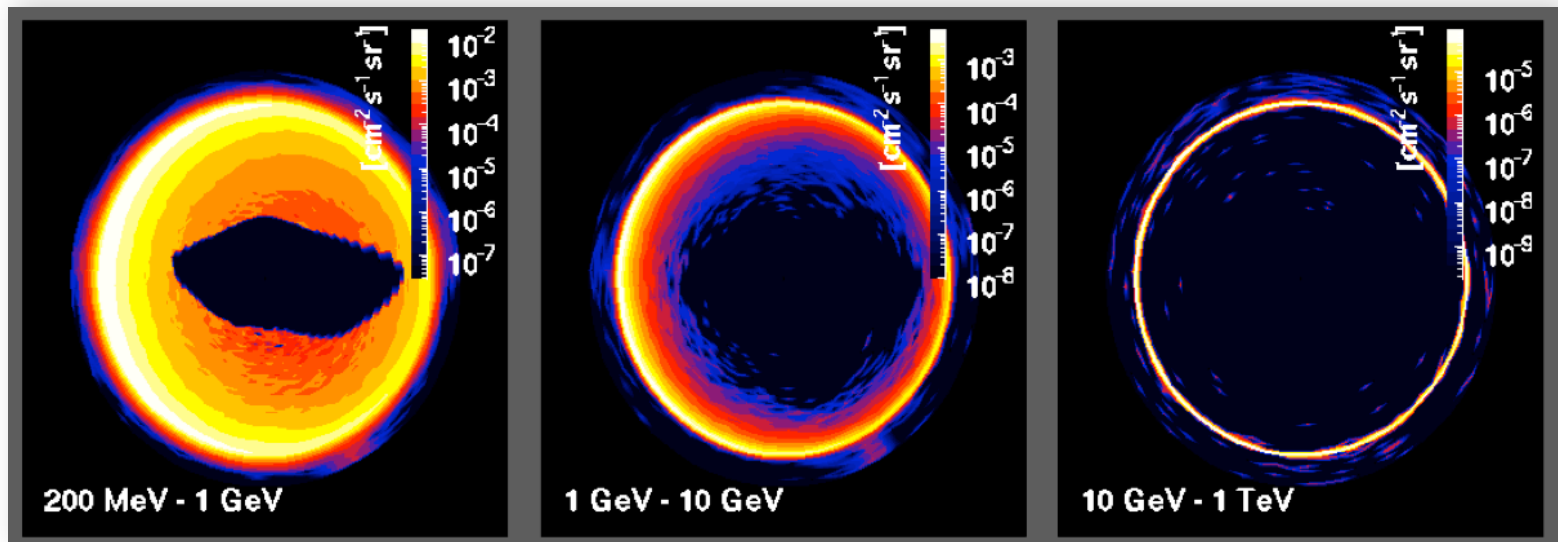
Example template with both sun and moon, using 1-year average exposure



Example template of sun using one year of actual exposure

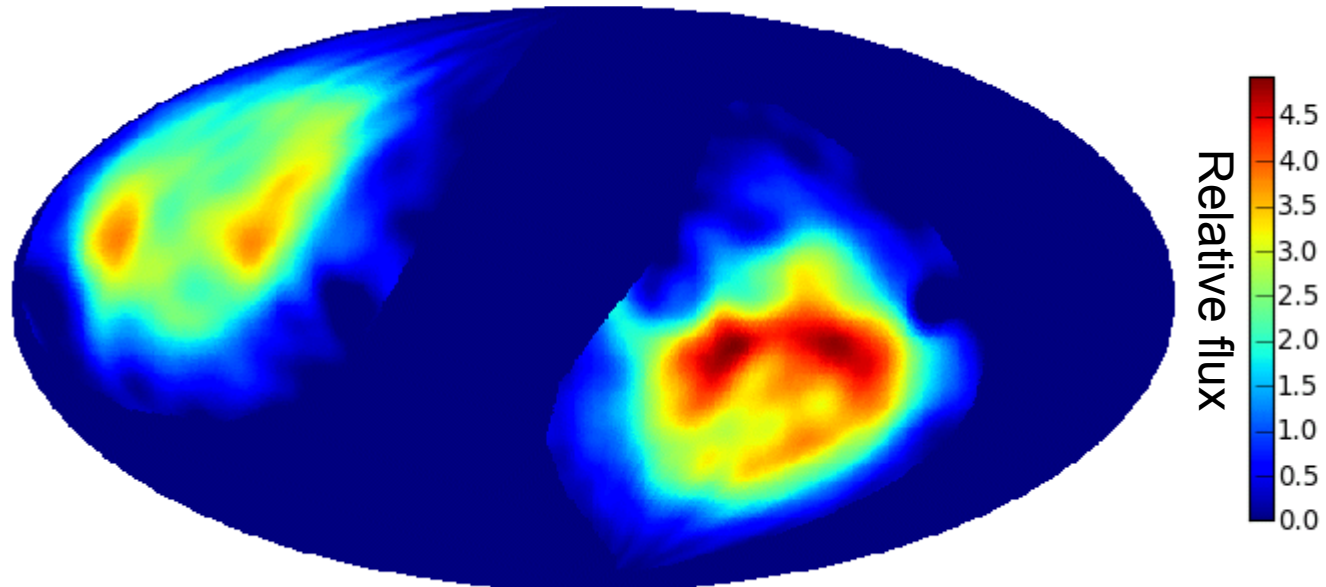
Atmospheric gamma rays

- The Earth's limb is *bright* in gamma-rays!
 - Secondary gamma rays from cosmic ray interactions in the Earth's atmosphere
 - At Fermi's altitude, the limb is ~ 113 deg from zenith
 - Far brighter than celestial sources
 - Need to remove limb gammas from analysis of celestial sources
 - Do geometry cut (standard recommendation)
 - e.g. cut on zenith angle



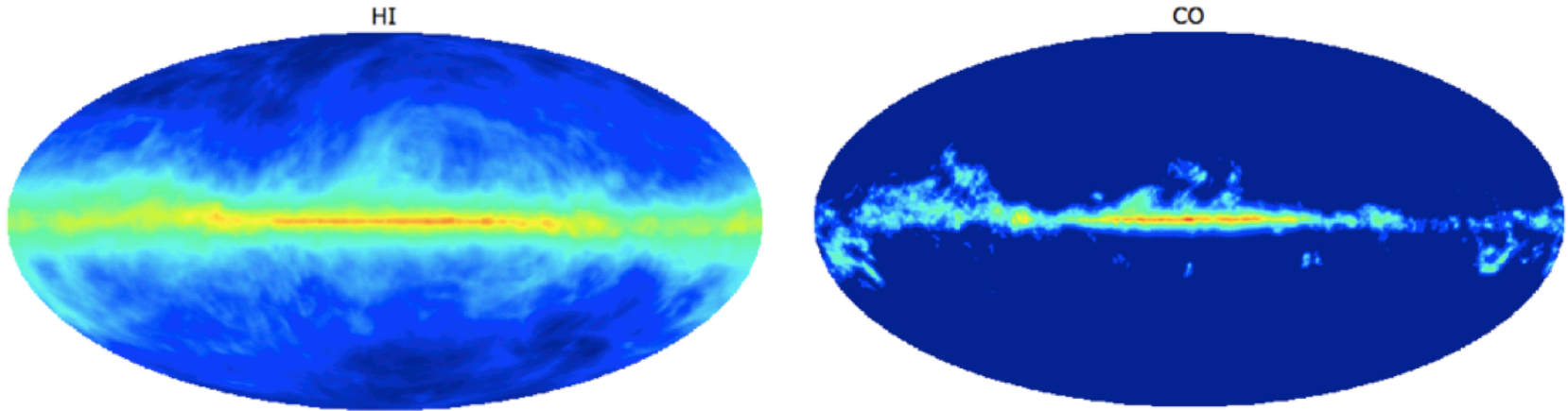
Residual Earth limb emission

- **Some leakage can happen even after excluding events close to the limb**
 - Residual limb photons can be seen at the celestial poles at low energies (low energy = large PSF)
 - Can be fitted as a separate background template
 - Time-variable contribution, so average contribution may not be appropriate for time-series analysis



Galactic Diffuse Emission

- Structure caused by cosmic rays interacting with Galactic gas and dust to produce gammas
 - Modeled with all-sky fit to GALPROP Galactic disk components over 30 energy planes
 - *Inverse Compton, HI, CO, Dark Gas, etc...*

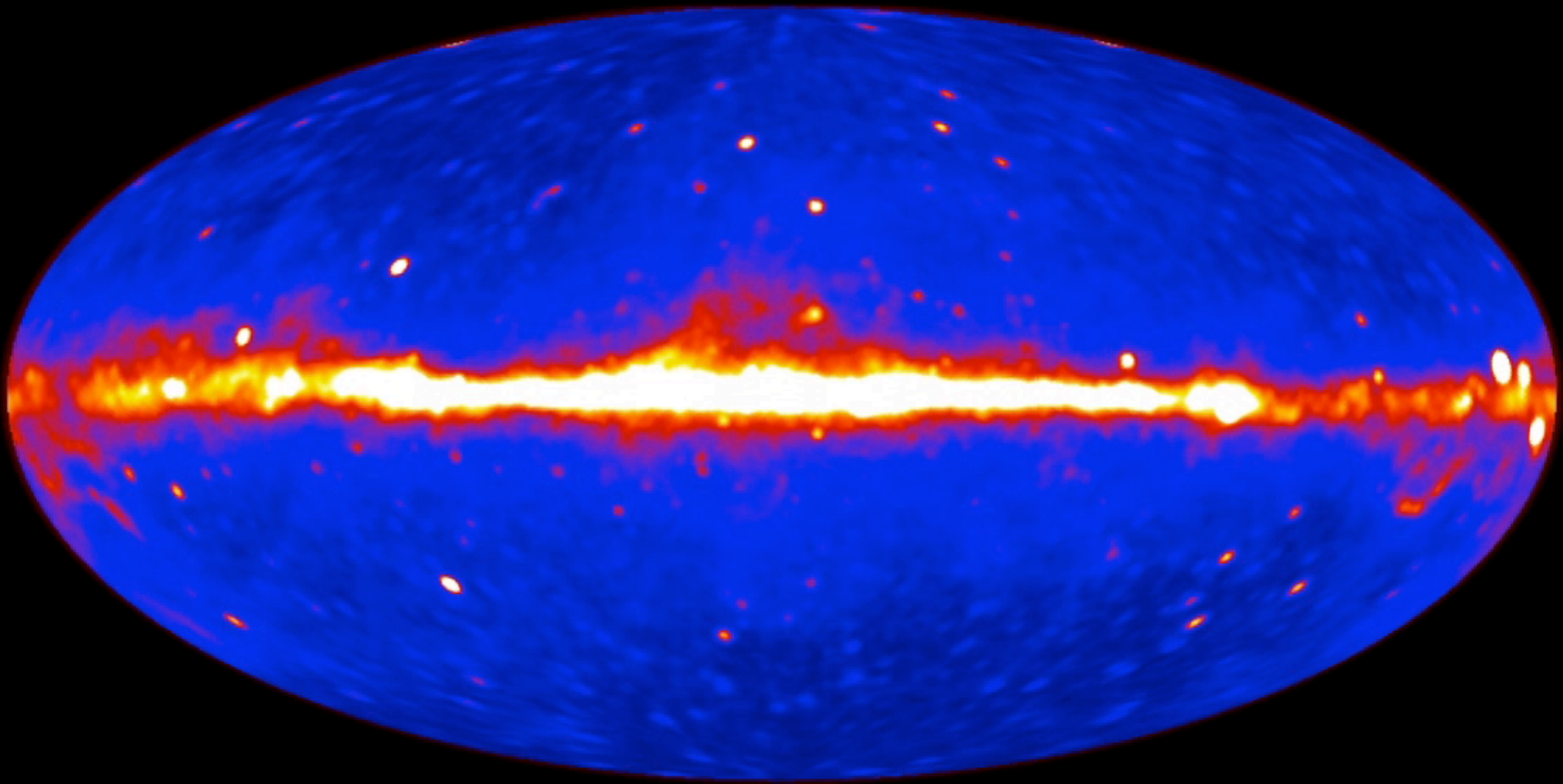


- Several extra spatial components must be incorporated into the model
 - *Loop 1 (structure near the Local Bubble that is clearly visible in Gamma Rays), northern spur*
 - *Fermi Bubbles, Cygnus region, Carina arm*

Discovery
by Fermi!



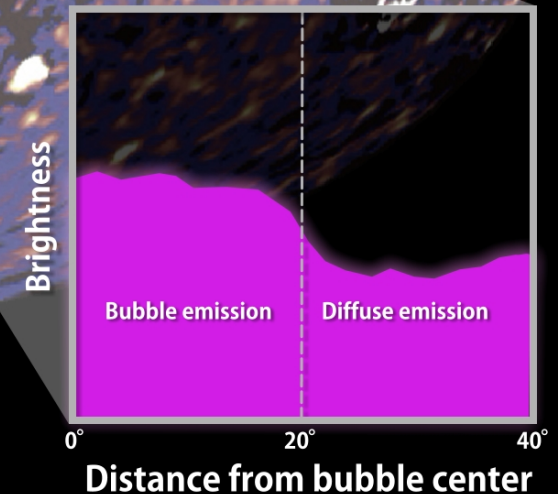
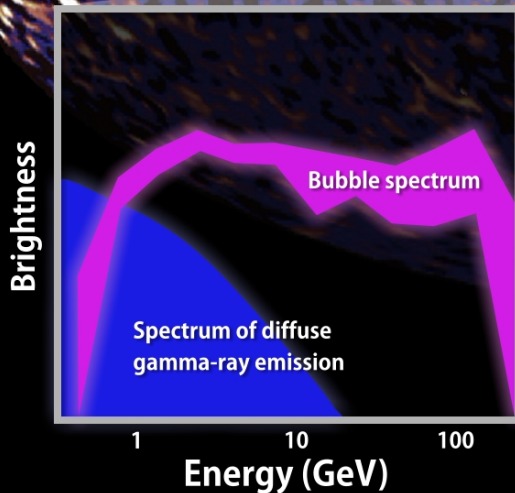
Fermi Bubbles



Bubble Detail

The bubbles display a harder (more energetic) spectrum than the diffuse emission.

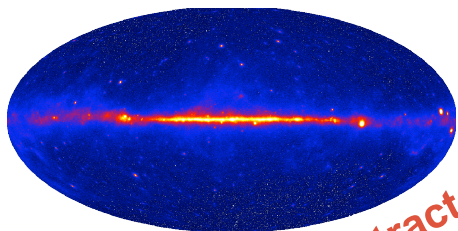
The bubbles display sharp edges (less than 2°), which suggests a sudden, impulsive event.



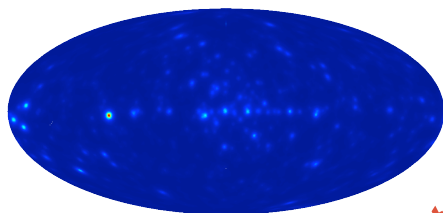
Take a look at Diffuse Model

Deriving the extragalactic diffuse spectrum

LAT Sky

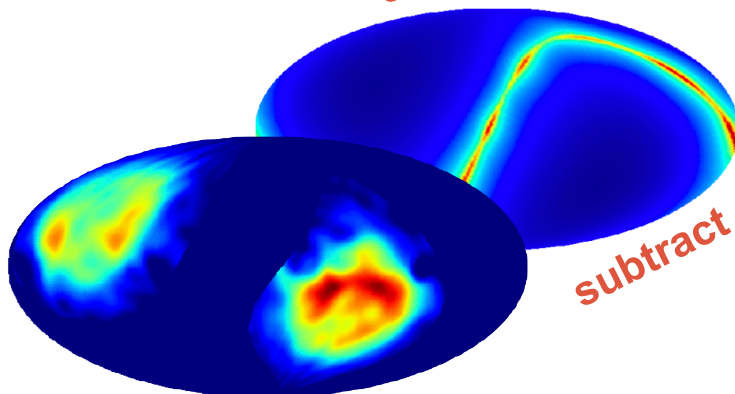


subtract



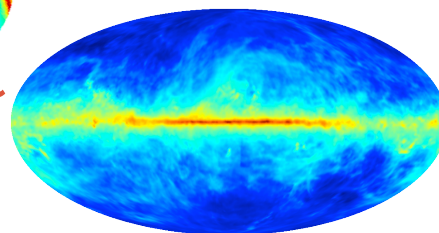
Point Sources

subtract



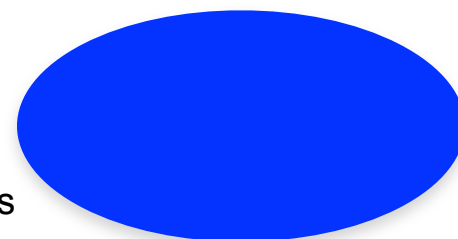
Large-scale residual
structures

subtract



Galactic Diffuse Components

leaves → Isotropic Diffuse Emission



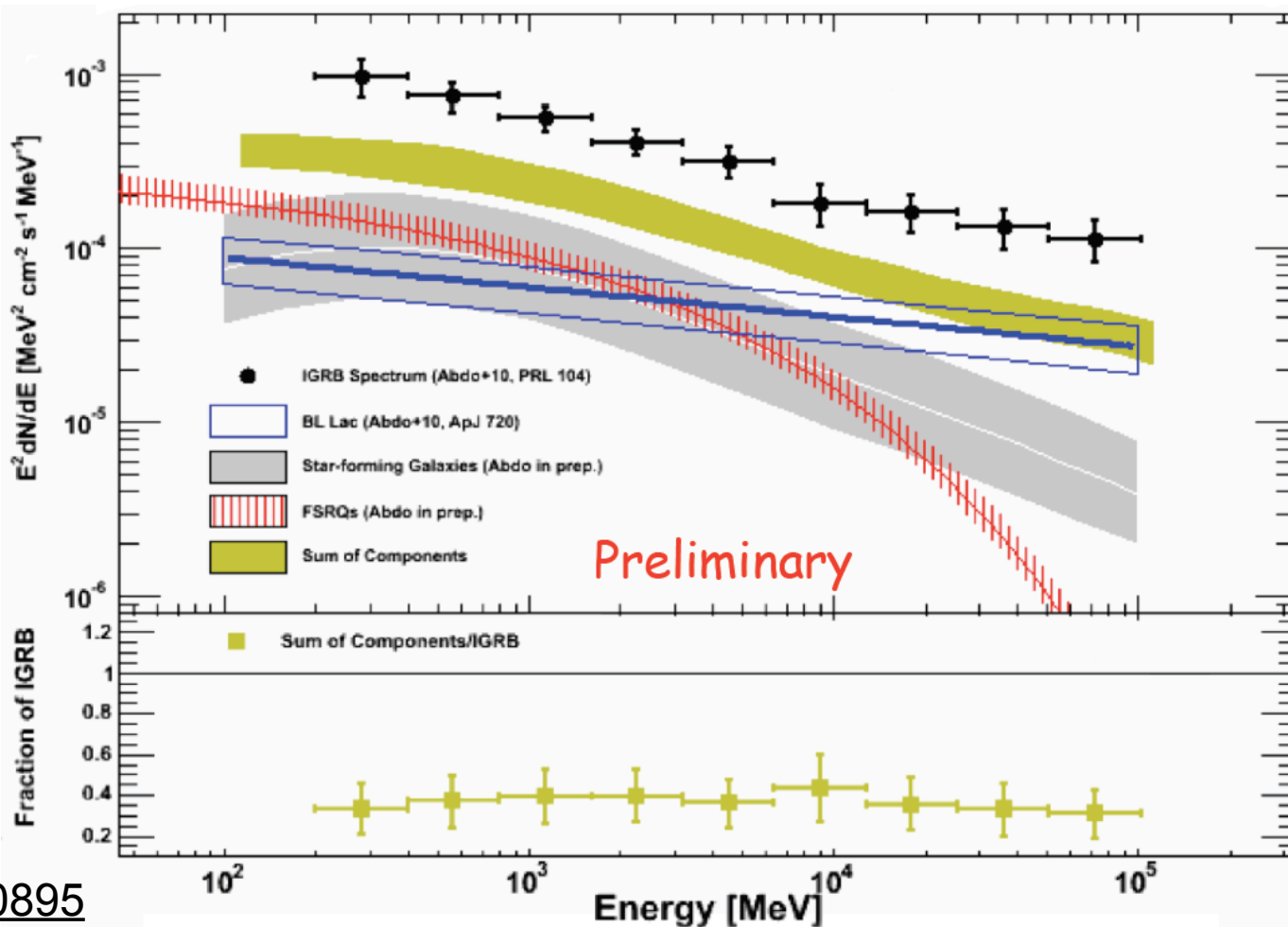
– Isotropic diffuse spectrum is a combination of:

- *Emission from unresolved extragalactic sources*
- *Residual charged-particle background*
- *Other signal?*

– Model the charged particles background to remove that signal

Isotropic Gamma-ray Background

- Much, but not all, of the IGRB is accounted for
 - May provide cosmological clues



Summary

- The LAT sees a large variety of different source types
 - Short and long timescales
 - Many different spectral forms
- One person's 'background' is another person's 'source of interest!'
- Separating point sources from each other and from the diffuse background is an on-going challenge
- Fermi is a significant discovery machine!
 - New Galactic Structures

Many unexpected sources

What's next?

Fermi Science Support Center

<http://fermi.gsfc.nasa.gov/ssc/>

High-level Documentation: <http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/>

Analysis Threads: <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/>

SciTools man pages: <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/references.html>

User Contributed Tools: <http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/>

LAT Data: <http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi>

Background Models: <http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>

All-sky Files: <ftp://legacy.gsfc.nasa.gov/fermi/data/lat/weekly/>

Low-Energy Data: <http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermille.html>

2FGL Catalog: http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/

GBM Data: <http://fermi.gsfc.nasa.gov/ssc/data/access/gbm/>

GBM Burst Catalog: <http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html>

Caveats: <http://fermi.gsfc.nasa.gov/ssc/data/analysis/caveats.html>